AD-754 411

ELECTROMAGNETIC COMPATIBILITY MANUAL

Joseph J. Fisher

Naval Air Systems Command
Washington, D. C.

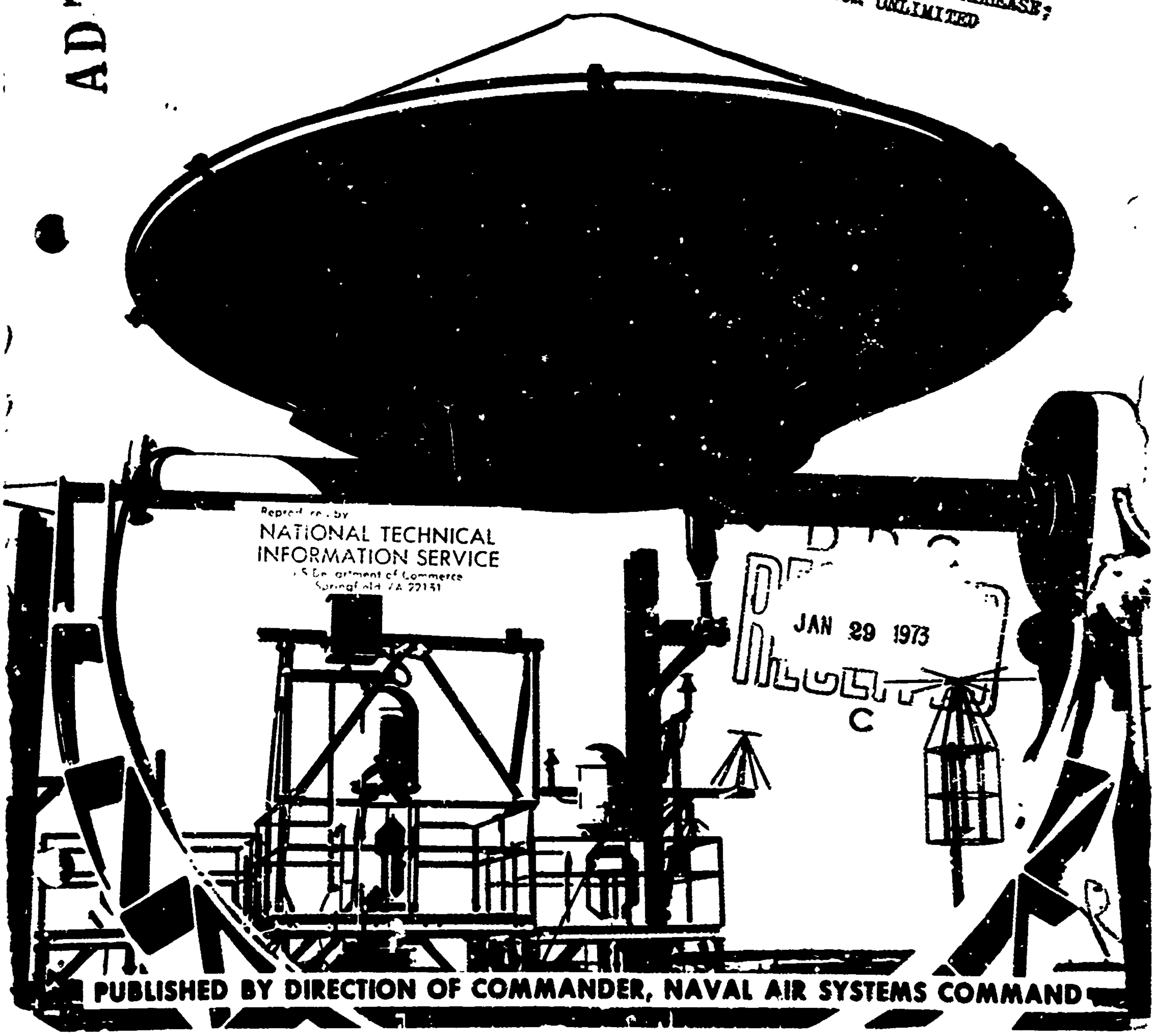
May 1972

NAVAIR 5335

NAVAL AIR SYSTEMS COMMAND

ELECTROMAGNETIC COMPATIBILITY MANUAL

MAY 1972



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PREFACE

This Electromagnetic Compatibility (EMC) Manual has been prepared by the Naval Air Systems Command in accordance with Department of Defense Directive 3222.3 of 5 July 1967, to provide information for the control or reduction of electromagnetic interference across the frequency spectrum.

The manual will be of interest to the electromagnetic community in government and private industry and has been divided into sections of interest to various levels within these organizations.

In general, the manual fosters common DoD - wide philosophies, approaches and techniques in the management, design, production, test, and operation of communications and electronics equipment. Of particular note is the information provided for maintaining EMC and lightning protection integrity in aircraft weapons systems now in the inventory.

The material in this manual, with its contributions for improvements in the state-of-the-art of electromagnetic compatibility, provides a reference on methods for the reduction of electromagnetic interference and accomplishing electromagnetic compatibility in and between aircraft weapons systems.

Joseph C. Kemp

JOSEPH C. KEMP
CAPTAIN, U. S. NAVY
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FOREWORD

As project engineer for this manual, I firmly believed that an unnecessary void existed in education, communications, and approach to the control and measurement techniques of electromagnetic interference.

This manual was prepared by the Naval Air Systems Command (Avionics Division) to fill that void in education and communications between engineers, and between engineers and management.

The manual was reviewed by American technical societies, various Government agencies, and private industry. That help is gratefully acknowledged.

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This project engineer is, in particular, indebted to the following individual reviewers (and many others whose names he could not recall).

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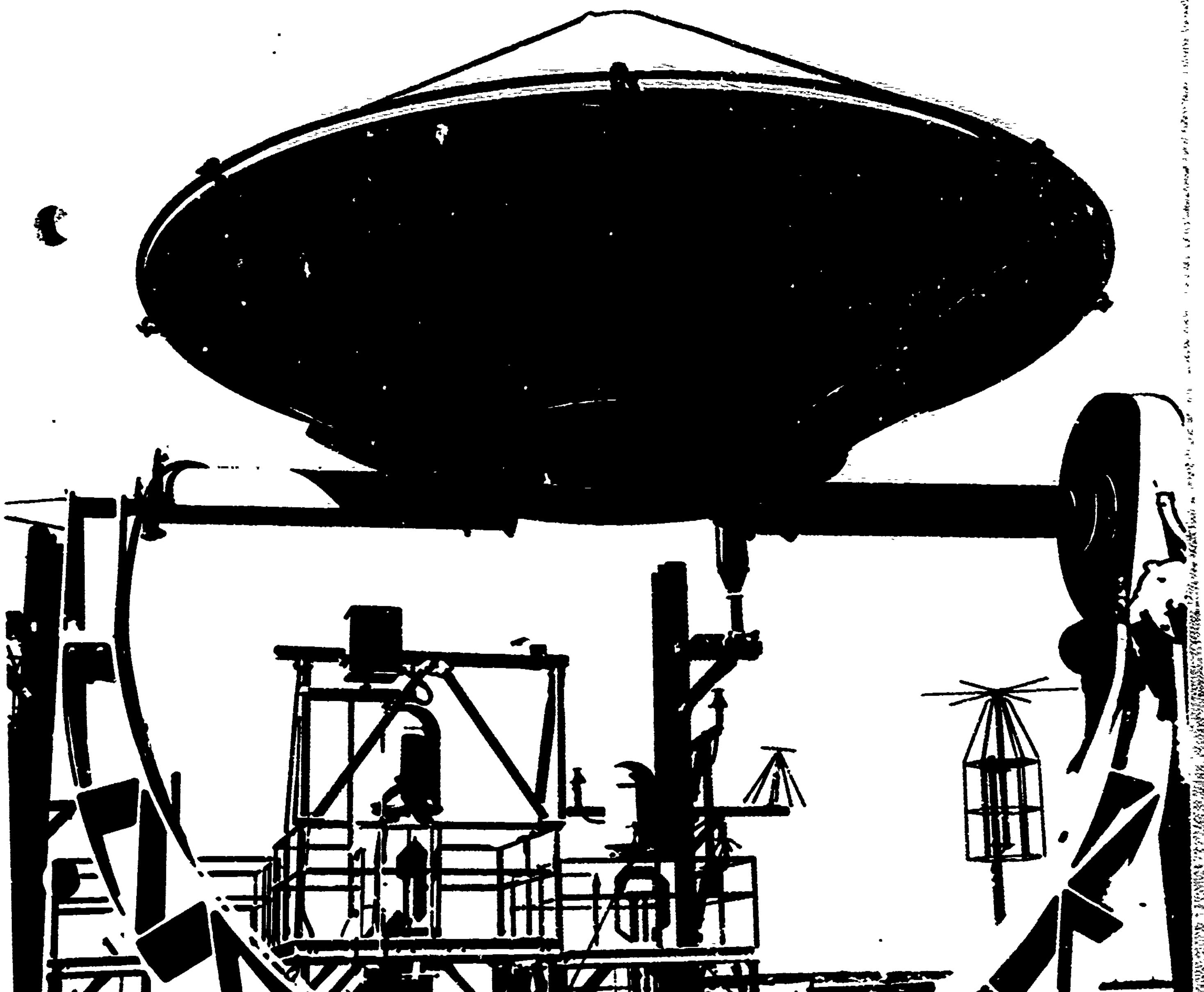
CHAPTER 1



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CHAPTER 1
INTRODUCTION TO THE NAVAIR EMC EDUCATIONAL PROGRAM

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BASIC DEFINITIONS

The accepted definition of "compatibility," according to the Merriam-Webster dictionary, is "to be able to exist together in harmony." The NAVAIR Electromagnetic Compatibility Educational Program describes electromagnetic compatibility (EMC) as the ability of avionic and electrical systems, equipments, and devices to operate in their intended electromagnetic environments, with a margin of safety and at design levels of performance without unacceptable degradation as a result of electromagnetic interference.

PROGRAM OBJECTIVE

The NAVAIR EMC Educational Program is based on the integrated DoD Electromagnetic Compatibility Program (EMCP) expressed in the Department of Defense Directive 3222.3 dated 5 July 1967 and in SECNAVINST 2410.1B dated 17 October 1967. The primary purpose of the EMCP is to ensure electromagnetic compatibility of all military communications-electronics equipments, subsystems, and systems during conceptual, design, acquisition, and operational phases.

As stated in the DoD directive, other objectives of the EMCP are:

A. Achievement of electromagnetic compatibility of all electronic and electrical equipments, subsystems, and systems produced and operated by components of the DoD in any electromagnetic environment. Operational compatibility is part of and the paramount focus of this objective.

B. Attainment of compatibility through built-in design rather than by remedial measures.

C. Fostering of common DoD-wide philosophies, approaches and techniques in the design, production, test, and operation of C-E equipments.

EMC IN AVIONIC SYSTEMS

An early example of the lack of EMC in military aircraft was described recently by Vice Admiral J. D. Arnold, Vice Chief, Naval Material Command. Admiral Arnold told some of his experiences when he was the Bureau of Aeronautics' representative at Lockheed: *It was my job to test fly, and accept aircraft which we were buying for the Navy. They were Willy-Victor II models (better known as the Pregnant Connie), early warning aircraft, and probably the most complex weapon system that existed, at least in naval aviation. The object of the exercise up to that time was to fly the airplane and check for conformance to speed and other performance specifications. During the test, we decided to do something that we hadn't done before. Although we did not have all the electronic technicians who would finally man that airplane, we turned everything on. Well, in about 45 minutes we rapidly started turning everything off, because it got so hot that you couldn't stay in the place. Not only that, but the height-finding radar and search radar interfered with each other, and so did some of the other systems. In other words, although each system had been checked out individually, when they were all plugged in together, they did not work.*

During World War II it became evident that the increased use of the spectrum by communications-electronics equipment and systems was creating new problems that reduced the effectiveness of the then new equipment. Not only in the combat zone but also on the home front, the plague of electromagnetic interference demanded that some action be taken to control unnecessary emissions and undesirable susceptibilities. Action on this resulted in a joint Army-Navy Specification, JAN-I-225, June 1945. It prescribed standard measurement methods for the frequency range of 150 kHz to 20 MHz. No limits were established but provisions were made to measure conducted and radiated interference. The specification was used in conjunction with specification AN-I-27, which was established as an early criterion for control of interference in aircraft electrical systems.

A single specification with limits and test methods was eventually developed for aircraft systems. In June 1950 a specification, MIL-I-6181, "Interference Limits and Tests: Aircraft Electrical and Electronic Equipment," was released. It was a significant advance in the coordination of interference control for aircraft systems. But MIL-I-6181 was directed toward the control of interference to voice communication receivers operating in the range of 2 to 30 MHz. Tactical communication systems moved into the VHF/UHF range, and various radar, ASW, navigation, recognition, missile guidance, data link, ECM, and other equipments made use of even higher frequencies in the electromagnetic spectrum.

At the same time, digital computers, encode/decode devices, displays, recorders, instruments, servomechanisms autopilots, fire control subsystems, and so forth brought added emphasis to the EMC aspects of the lower frequencies of the electromagnetic spectrum. To cope with the burgeoning

electronic complex, MIL-STD-826, "Electromagnetic Interference Test Methods and Test Requirements," was developed for use by engineers in performing EMC tests on equipments in the range of 30 Hz to 20 GHz.

Another development was MIL-E-6051, "Electromagnetic Compatibility Requirements, Systems." The purpose of this specification is to provide a way to demonstrate overall compatibility of a subsystem or an entire aircraft weapon system. This is accomplished by scheduling the operation of all receptors and emitters in selected modes to assure that operation of any subsystem or equipment does not degrade the performance of any other subsystem or equipment below specified limits.

Mention must be made of the new generation of EMC documents, the 460 series of military standards, which are being developed to unify and standardize the EMC requirements of the DoD components. It is planned that eventually this series of standards will supersede older EMC specifications which no longer meet current requirements. The 460 series is now made up of the following standards:

MIL-STD-461 Electromagnetic Interference Characterisitcs, Requirements for
MIL-STD-462 Electromagnetic Interference Characteristics, Measurement of
MIL-STD-463 Definitions and Systems of Units, Electromagnetic Interference Technology
MIL-STD-469 Radar Engineering Design Requirements, Electromagnetic Compatibility

Additions to this series are being prepared. Eventually, the series will cover all pertinent aspects of EMC.

The complexity of a modern weapon system is shown in Figure 1-1, the cockpit instrumentation and control panels of a typical attack aircraft. Most of the instruments and individual control panels are supported by communications-electronics equipment and much of this is remotely located. This adds up to an overwhelming package. But even this is small when compared with the instrumentation and controls required for certain special-purpose aircraft. Modern aerospace systems have become so complex that there are thousands of potential sources of incompatibility. In spite of carefully planned EMC designs and controls, hundreds of incompatibilities appear during system design and development. Most of these are finally eliminated before the Navy accepts the aircraft from the contractor. Detecting and correcting such large numbers of incompatibilities, or validating their existence if predicted, requires elaborate testing and measurement facilities, including a large anechoic test chamber capable of containing an entire aircraft. Such a chamber is shown in Figure 1-2. Pyramidal shaped anechoic material covers all surfaces of this chamber. The anechoic material on the bottom surface is under the nonconductive flooring material.

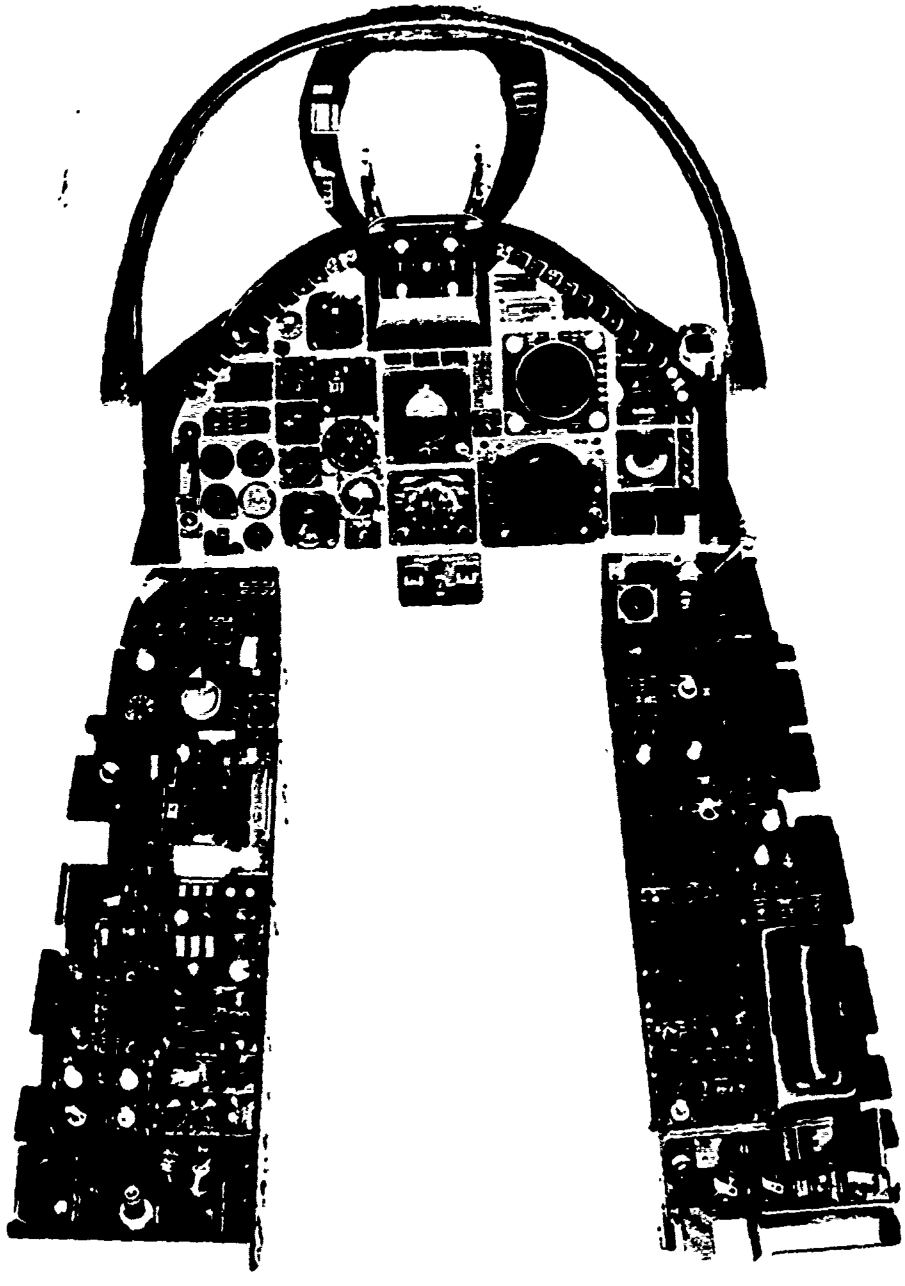

FIGURE 1-1 TYPICAL ATTACK AIRCRAFT COCKPIT INSTRUMENTATION AND CONTROL

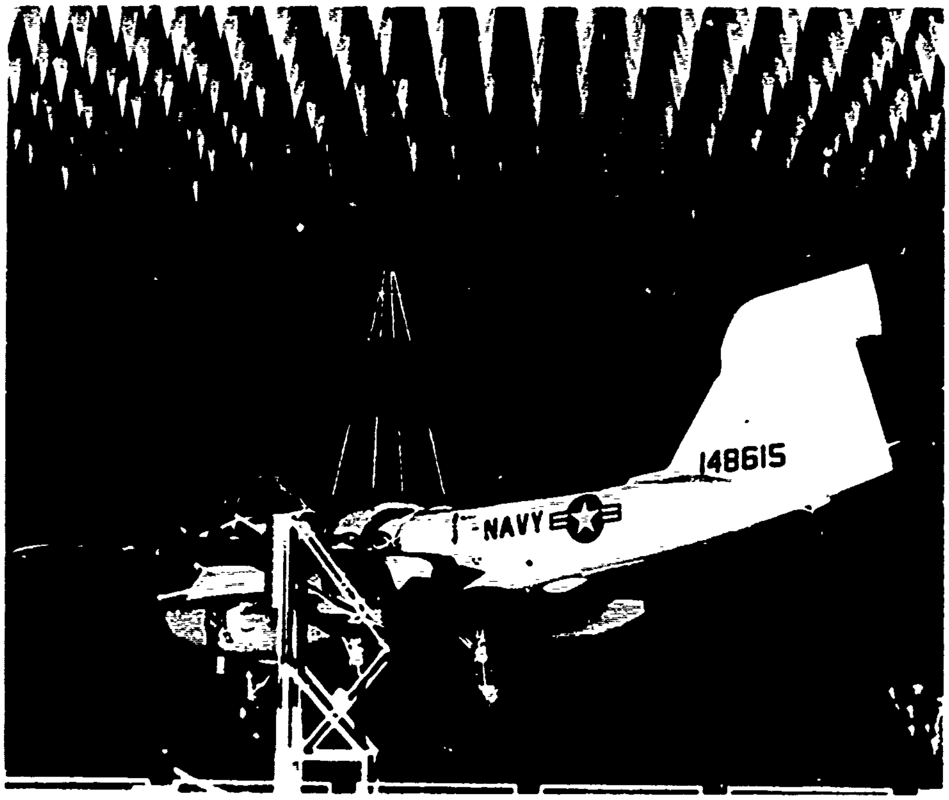

FIGURE 1-2 LARGE ANECHOIC TEST CHAMBER

RELATED PROGRAMS

The DoD Electromagnetic Compatibility Program (EMCP), as presently constituted, deals primarily with the electromagnetic compatibility between electric and electronic equipments and systems. However, persons interested in the EMCP should also be aware of related programs dealing with electromagnetic compatibility between electronic devices and personnel, ordnance, and fuels. The programs are respectively RADHAZ, HERO, and SPARKS.

The radiation hazards to personnel (RADHAZ) program is intended to protect personnel from physiological and pathological effects of non-ionizing radiation. As radar and communication transmitter power levels have increased, there has been more concern about protection of personnel from the hazards created by these high-power electromagnetic emissions. The biological effects of radiation are primarily due to the rise in body temperature as the radio frequency energy is translated into heat. This is a function of the power density of the radio waves and their penetration into the body. Penetration is an inverse

function of frequency but is still significant in the microwave region. Certain parts of the body such as the eyes, testes, gall bladder, urinary bladder, and portions of the gastro-intestinal tract are more susceptible than others to microwave radiation. The potential hazard to the eye is one of the most critical aspects of microwave radiation, and damage to its lens is irreversible. The damaged cells slowly lose their transparency; sometime after exposure cataracts may form.

The American Standards Institute's standard C95.1-1966, "Safety Level of Electromagnetic Radiation," concerning personnel, states: "For normal environmental conditions and for incident electromagnetic energy for frequencies from 10 MHz to 100 GHz, the radiation protection guide is 10 mW/cm^2 (10 milliwatts per square centimeter) as averaged over any possible 0.1-hour period." It is recommended that warning signs be posted in any areas where this level may be exceeded.

The HERO program is concerned with RF hazards to ordnance, such as the accidental firing of electrically detonated missiles, rockets, proximity fuses, squibs, primers, and detonators. Concern over electromagnetic radiation hazards to electro-explosive devices (EEDs) arises from the fact that electrical leads to an EED can, under certain conditions, act as an effective antenna. There have been instances where RF power picked up by the leads has caused an inadvertent firing. Military and range directives on the subject of EED protection require that precautions be taken to prevent inadvertent firing under the most severe RF environment that may be encountered in the field. Some of the precautions include shielding of leads, twisting of leads, placing filters in series with leads, using balanced circuits, and using relatively insensitive EEDs. Even these precautions do not provide completely dependable protection under all conditions.

Hazards of electromagnetic radiation to fuels is the subject of the SPARKS program. A hazardous condition exists when an aircraft is being fueled near high-powered communications or radar equipment which is operating on shipboard, at ground bases, and even on the aircraft or adjacent aircraft. Present efforts are being directed toward the elimination of conditions conductive to arcing during fuel handling operations. Safe-distance tables are available to show the minimum safe separation between RF transmitters and fuels and fueling operations.

PURPOSE OF THE NAVAIR EMC MANUAL

This manual has been prepared to serve as a textbook and reference for the formal classroom presentation of NAVAIR EMC Educational Courses. It will be supplemented with lecture notes prepared by the instructors, and with various training aids and demonstrations suitable for the material being presented and the particular interests of the class personnel.

It is intended that the course will be offered to the following:

1. Management personnel representing the military establishment and industry. This will include NAVAIR plant representatives.

2. Design and planning personnel concerned with NAVAIR weapon systems. Contractors and NAVAIR will be represented, including NAVAIR plant representatives.

3. EMC control, test, and evaluation personnel employed by contractors and by Navy field activities, such as the Naval Air Test Center (NATC), the Naval Air Development Center (NADC), and the Naval Weapons Laboratory (NWL). This will include NAVAIR plant representatives.

4. Maintenance and operations personnel from NAVAIR and from operational groups.

The chapters of this manual were prepared to satisfy the requirements for a course in EMC for each of these four groups. Each chapter covers a specific EMC segment, and the curriculum for each group will emphasize certain chapters. Some chapters will be covered in full by the instructor, others will be covered in summary form. The plan for this emphasis is shown in Table 1-1.

COVERAGE OF SUBJECT BY GROUPS

GROUP	CHAPTER																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
M	X	X	X	X	X	X	X	X	X	O	O	O	O	O	O	O	O	O	O
D&P	X	O	O	O	X	X	X	O	X	X	X	X	X	X	X	X	X	X	O
CTE	X	O	O	O	X	X	X	O	X	X	X	X	X	X	X	X	X	X	O
M&O	X	O	O	O	X	X	O	X	O	O	X	X	X	X	O	O	X	X	X

M - Management (Middle- and Upper-Level)
D&P - Weapon System Designers and Planners
CTE - EMC Control, Test, and Evaluation Personnel
M&O - Maintenance and Operational Personnel
X - Covered in full
O - Covered in summary form

TABLE 1-1 CHAPTER INTEREST GUIDE

TRAINING OF MANAGEMENT PERSONNEL

As indicated by Table 1-1, the first nine chapters of the manual are addressed primarily to middle- and upper-level management. The material presented is designed to indicate to management the importance of EMC in obtaining acceptance of equipment for use in its intended environment. Chapter 8 provides some of the material necessary to assist an instructor in giving a summary of Chapters 10 thru 19. The first nine chapters are organized to stress the following:

1. WHY EMC is needed.
2. HOW to implement an EMC program organizationally.
3. WHAT the general technical problems are.
4. WHAT government EMC requirements and specifications are contractually imposed.

TRAINING OF DESIGN AND PLANNING PERSONNEL

The chapter emphasis shown in Table 1-1 for these personnel permits the instructor to:

1. Review engineering fundamentals related to attaining EMC.
2. Discuss emission and susceptibility characterisitcs of component parts, and the effects of these electromagnetic characteristics in functional circuits.
3. Discuss techniques of grounding, bonding, shielding, and filtering.
4. Discuss equipment packaging and interfacing.
5. Discuss the development of trade-offs in avionic system design.
6. Indoctrinate design and planning personnel to be aware of EMC.
7. Place emphasis on EMC contractual requirements, including requirements for EMC control and test plans.
8. Conclude with presentations and discussions on applicable EMI/EMC tests and case histories involving avionic EMC problems, including corrective action taken.

The appropriate portion of Chapter 8 may be used to assist the instructor in summarizing Chapter 19.

TRAINING OF EMC CONTROL, TEST, AND EVALUATION PERSONNEL

The interest of the EMC control, test and evaluation personnel closely parallels that of the design and planning personnel. The same chapters will be emphasized for both groups. The difference of interest that does exist will be accommodated by slanting the material in the classroom presentation. Both groups are interested in EMC characteristics of parts and equipment and in the engineering fundamentals for good EMC design. However, the designers and planners will be more interested in control plans while the control, test and evaluation personnel will be more concerned with the details of test plans and measurement procedures, requiring a well-planned classroom demonstration of the measurement procedures required by military EMC standards.

TRAINING OF MAINTENANCE AND OPERATIONAL PERSONNEL

These are Navy personnel who have been trained to be proficient in the operation and maintenance of Navy weapon systems. Such training does not, at present, include a consideration of the problems associated with EMC. Using the chapter emphasis shown in Table 1-1, this course should provide the awareness and indoctrination in EMC that is required of personnel working with the complex weapon systems coming into use. Chapter 8 provides material for use by the instructor in summarizing Chapters 9, 10, 15, and 16.

The group should receive a presentation on the two phases of compatibility engineering, spectrum engineering and design for EMC, including a review of interference sources and methods of coupling into susceptible devices. There should be a detailed discussion of the mechanics of susceptibility so that operational personnel will be able to identify the source of any degradation of system performance and eliminate this degradation by proper operating techniques or by requesting assistance from maintenance personnel.

Maintenance personnel should be made aware of typical EMC design features incorporated into electronic systems and of their responsibility for taking proper maintenance action to insure the continued maximum effectiveness of these design features throughout the life of any system they maintain.

Atmospheric interference should be discussed so that operational personnel will be aware of the detrimental effects on operational performance and of certain measures which will reduce these effects.

In anticipation of the time when maintenance facilities will be instrumented for system checkout from an EMC standpoint, there should be an intensive coverage of test equipment and EMC measurement techniques by the course instructor. The philosophy of EMC maintenance should be explained, with examples of incompatibility. It should be emphasized that the EMC concept is new in the maintenance domain, because current directives on EMC in the 2400 series of instructions and notices are addressed to headquarters level and have not reached the maintenance or operating personnel level.

REFERENCES

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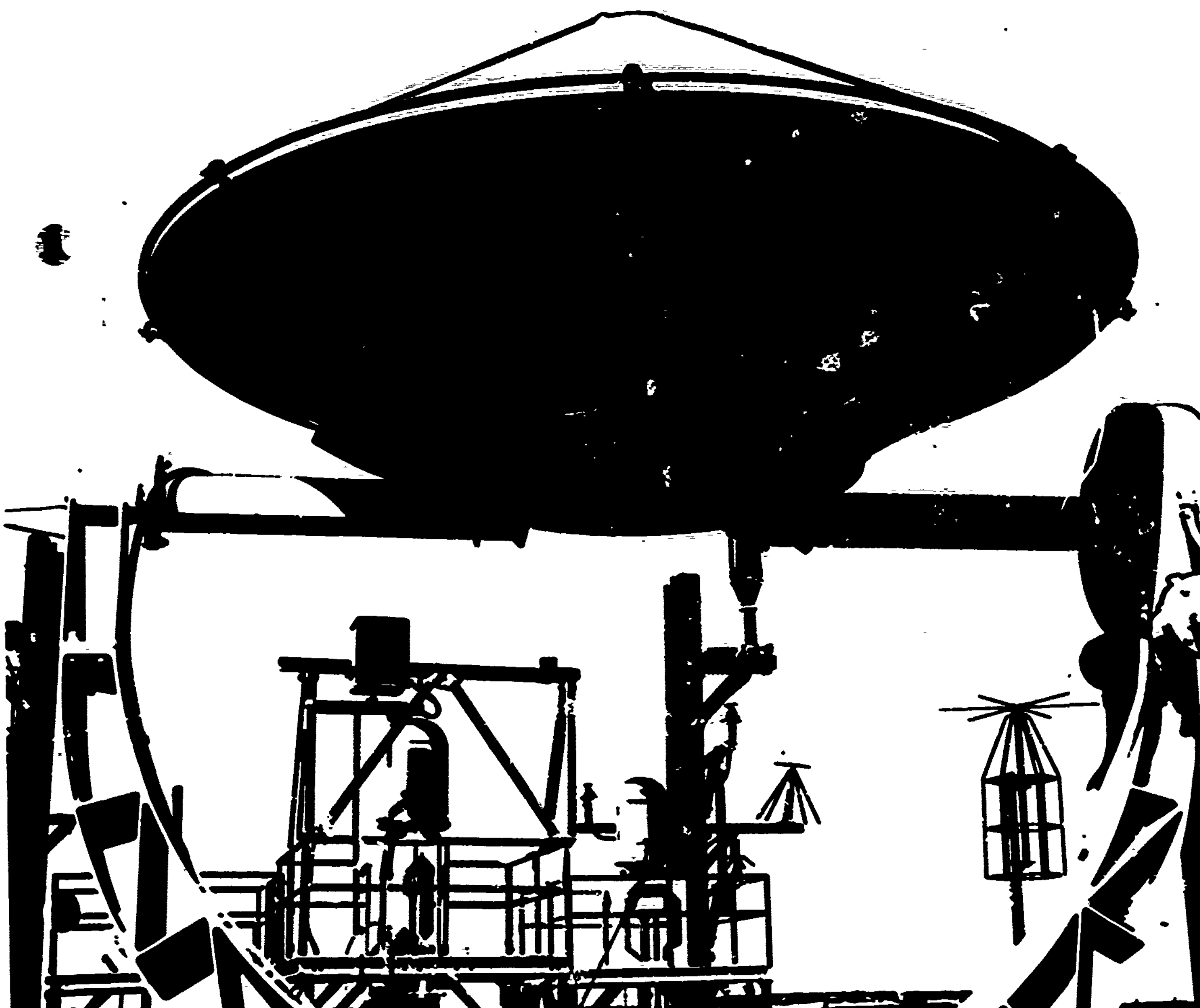
ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 2



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CHAPTER 2
THE DoD EMC PROGRAM

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ILLUSTRATIONS

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DEPARTMENT OF DEFENSE ELECTROMAGNETIC COMPATIBILITY PROGRAM

The Secretary of Defense promulgated, by means of Department of Defense Directive 3222.3 of July 5, 1967, an integrated Department of Defense program designated the "DoD Electromagnetic Compatibility Program."

For purposes of the DoD EMC Program, electromagnetic compatibility is defined as the ability of communications-electronics equipments, subsystems, and systems to operate in their intended operational environment without suffering or causing unacceptable degradation because of unintentional electromagnetic radiation or response.* It does not involve a separate branch of engineering but emphasizes improvement of electrical and electronic engineering knowledge and techniques to include all aspects of electromagnetic effects. The DoD EMC Program approaches the compatibility problem from two aspects: that of operational compatibility, and that of design compatibility.

Operational compatibility consists of frequency management, operational concepts, and doctrinal procedures to accommodate each legitimate claimant to a frequency assignment without deleterious interaction with other legitimate claimants to spectrum occupancy. Operational compatibility is achieved by the application of equipment capabilities, sound frequency management, and clear concepts and doctrine to maximize operational effectiveness in homogeneous or heterogeneous environments of equipments. It relies heavily upon initial design compatibility.

Design compatibility is the quality or characteristic built into a component, equipment, subsystem, or system which permits it to function in harmony with other components, equipments, subsystems, or systems. Design compatibility is achieved by including in all devices that radiate or receive electromagnetic energy features to control the generation of or response to undesired signals, and to enhance operating capabilities in the presence of natural or man-made electromagnetic interference.

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*This definition, quoted from DoD Directive 3222.3, excludes situations where intentional radiation is concerned. Variations on this definition are in use by the various branches of the services. For the purpose of this manual, electromagnetic compatibility will include effects of intentional as well as unintentional electromagnetic radiation and response.

Electromagnetic compatibility is created most effectively when it is considered in the initial planning and design stages rather than after-the-fact. EMI problems are subject to an organized and orderly attack, and the objectives of the DoD EMC program include attacking the problem at all levels. The purpose of the DoD EMC program is to provide management and technical direction to ensure electromagnetic compatibility of all military communications-electronics (C-E) equipments, subsystems, and systems during concept formulation, design, acquisition, and operational phases. The Directive assigns specific or joint responsibilities to the military departments for leadership and implementation in each of the program areas. Program areas considered under DoD Directive 3222.3 include: (1) standards and specifications, (2) measurement techniques and instrumentation, (3) education for EMC, (4) data base and analysis capability, (5) equipment and system design, (6) concepts and doctrine, (7) operational problems, and (8) test and validation.

OBJECTIVES OF DoD EMC PROGRAM

The stated objectives of the DoD EMC Program include achievement of electromagnetic compatibility in an operational electromagnetic environment of all electronic and electrical equipments, subsystems, and systems produced for and operated by components of the Department of Defense. Operational compatibility is part of, and the paramount goal of, these objectives. A second objective is the attainment of compatibility through initial design rather than by applying remedial measures. Military operations have shown that lack of electromagnetic compatibility is a high-risk condition. It is no longer technically or economically feasible to base the design of each C-E device on self-centered requirements, then make alterations, modifications, or external changes to the design to make it compatible when it is operated as a part of a total weapon system. EMC prediction and analysis saves money and time when applied to the original design. A third objective is the fostering of common DoD-wide philosophies, approaches, and techniques in the design, production, test, and operation of C-E equipments and systems.

Relationship to Other Activities

Electromagnetic compatibility problems are common to all users of the electromagnetic spectrum. A successful EMC Program must consider and serve all who share in the allocation and use of the spectrum. Within the constraints of national security and the availability of funds and facilities, the capabilities attained under the DoD EMC Program shall be made available to other Government agencies and the civilian community.

Insight into the military-civilian interplay can be obtained by tracing one aspect of the VHF/UHF allocation. With the coming of commercial TV, the military had to vacate much of the VHF spectrum. This, for example, required the Navy to move many of its VHF tactical and administrative channels into the UHF range. The VHF equipments were replaced with UHF equipments in the 225-400 MHz range, which in turn introduced compatibility problems not yet

solved. The military is required to silence its 220-225 MHz radars within 200 miles of certain land areas to avoid interfering with civilian TV and NASA telemetry. These radars are also a constant and troublesome source of interference to UHF military communications. Meanwhile, TV broadcasting continues to occupy 6 MHz per channel in a portion of the spectrum well suited to other uses, with such diverse radio services as public safety, aeronautical navigation and communication, meteorological and space telemetry, and military radiolocation and communication interspersed between TV channels.

In addition to the compatibility problems common to users of the spectrum, attention must also be directed to electromagnetic side effects involving other activities. For instance, energy from a high-power microwave source such as a radar can cause thermal damage to biological tissue. High-power klystrons and high-voltage cathode ray tube equipments such as TV can emit dangerous X-rays. Magnetic fields associated with magnetrons and traveling-wave tubes can upset navigation or detection systems that use earth magnetism. In addition to the detrimental effects of electromagnetic radiation upon nonusers of the spectrum, the converse must also be considered. Equipments not normally thought of as users of the spectrum, such as medical diathermy, induction heaters for metal working, dielectric heaters for forming plastic or bonding plywood, ultrasonic devices, arc welders, and automotive ignition must be considered part of the EMC problem.

Relationship to Other Programs

Electronic Countermeasures (ECM) Programs, Electromagnetic Pulse (EMP) Programs, Hazards of Electromagnetic Radiation to Ordnance (HERO) Programs, and Radiation Hazard (RADHAZ) Programs are all involved in specific aspects of electromagnetic radiation. Their existence as separate programs is predicated either on military requirements or on overriding urgency due to danger to personnel. As the DoD EMC Program progresses, it should augment, be used by, and in some instances be integrated with these programs. Advances in electromagnetic compatibility should denote basic advances in electromagnetic technology in general. These advances should be shared among all programs. These other DoD programs shall be so conducted that, as a minimum, equipments and systems developed for their special purposes meet all applicable EMC standards.. The EMC community should be alert also for techniques developed in other programs that have EMC application. For example, antijam techniques developed to reduce the susceptibility of an electronic sensor to deliberate hostile jamming are also likely to be effective against unintentional interference.

DoD EMC PROGRAM AREAS

The DoD EMC Program objectives encompass 8 areas applicable to defense agencies in general and to the military departments in particular. In four R&D oriented areas, responsibility for leadership and preparation of a coordinated plan has been assigned to a specific military component as shown in Table 2-1.

TABLE 2-1 Assignment of Responsibility for the Eight Areas of the DoD EMC Program

DoD Program Area	Army Responsibility	Navy Responsibility	AF Responsibility	DDR&E/JCS Responsibility
1. Standards and specifications	Assist Navy as necessary	Prepare with assistance of other components	Assist Navy as necessary	DoD review in January each year
2. Measurement techniques and instrumentation	Prepare with assistance of other DoD components; coordinate with areas 1, 4, and 5	Assist Army as necessary	Assist Army as necessary	DDR&E review in May each year
3. Training and education	Each DoD component prepare and conduct own program; consult with other components as necessary			No formal review guidance
4. Data base and analysis capability	Assist Air Force as necessary	Assist Air Force as necessary	Prepare coordinated plan for development of EMC analysis capabilities and use of data bases; coordinate with other plans (areas 1, 2, and 6), and with JCS plan for data base collection	DDR&E and JCS review plan in October each year and designate specific components to implement portions of it. JCS develop the joint plan for collection of data base
5. Design for EMC	Each component develop own plans and programs			Coordinate with other programs as necessary
6. Concepts and doctrine	Each component develop own plans and programs			JCS submit concepts and doctrines for joint military operations to ECAC for analysis of their impact on EMC
7. Operational problems	Each DoD component develop own procedures for detecting, reporting, and correcting internal operational EMC problems			JCS develop procedures to detect and report joint operational problems
8. Test and validation	Develop DoD plan, with assistance of other DoD components; coordinate with other plans (1, 2, and 4)	Assist Army as necessary	Assist Army as necessary	DDR&E and JCS review plan in May each year, and, if required, designate specific DoD components to implement portions of it

For example, the Air Force is assigned the task of developing a coordinated plan for EMC analysis and the use of EMC data bases.

Standards and Specifications

The DoD EMC Program calls for the preparation, consolidation, updating, and definitive promulgation of military standards and specifications relating to EMC. The standards and specifications area of the EMC Program requires:

1. Development of adequate and useful military standards and specifications for design, development, procurement, production, test, measurement, and other processes related to EMC.
2. Required establishment or correction of standards and specifications for EMC shall be performed promptly.
3. All DoD components shall adhere to all EMC standards and specifications for the applicable operational C-E equipments, subsystems, and systems unless adherence is duly waived.
4. Authority for waiver of any of the EMC Program standards and specifications shall rest at a level determined by the Secretary of the Military Department or Agency Director concerned for intra-service equipment environments. Waivers shall be made with discretion to prevent evasion of EMC standards and specifications.

Measurement Techniques and Instrumentation

The future of electronic design and electromagnetic analysis depends directly upon use of the best instruments and techniques. These are the basic tools of electronic and electrical engineering. Tests and measurements made in determining compliance with standards and specifications indicate the degree of success in equipment design. Measurements made in the field or in simulated environments establish the bases for confidence levels of analytical predictions.

Every effort should be made to develop reliable measurement techniques and equipment with the sensitivity, accuracy, range, and stability required to provide meaningful electromagnetic data and to facilitate the extension and application of EMC standards and specifications. Automatic control of all electronic measurement techniques and instruments will be used to the maximum practical extent to reduce operator errors and measurement costs.

EMC Education

An effective education program by the military departments is needed to make persons aware of the effects of EMC. All persons concerned with concepts formulation, design, development, production, test, operational use, and maintenance of military C-E equipments should apply EMC awareness to their tasks. The EMC Education Program will provide for:

1. Training of program managers, designers, and engineers in design and production methods and techniques for achieving electromagnetic compatibility
2. Training of operating and maintenance personnel in field techniques to optimize EMC.

3. Emphasis on EMC engineering as a refinement and much-needed improvement in basic electronic and electrical engineering techniques.

Data Base and Analysis Capability

The DoD EMC Program provides for the acquisition of effective data bases and mathematical and statistical tools for electromagnetic analysis of any C-E component, circuit, equipment, subsystem, system, environment, concept, or doctrine, and the ability to apply these tools to predict, prevent, and correct incompatibilities. The data base and analysis capability will require:

1. A DoD-wide data collection and verification plan to ensure complete and current data bases adequate to the description of any probable C-E environment in significant technical and operational detail.

2. Common data processing and analytical techniques to provide rapid and timely summaries of data and analyses of equipments within known or expected environments, site selection and evaluation, analyses of concepts and doctrine for the use of C-E equipment in support of military operations, and solutions of existing operational problems.

The functions of frequency management have a strong influence on operational compatibility and require data base and analysis support. DoD Directive 4650.1, "Management and Use of the Radio Frequency Spectrum," assigns responsibilities in this area. The DDR&E and the Chairman, Joint Chiefs of Staff, or their Designees for the EMC Program ensure that adequate data base and analysis support is provided by ECAC for the Department of Defense.

Electromagnetically Compatible Design

The DoD EMC Program objective in the design area is research, development, test, and evaluation (RDT&E) to evolve techniques, circuits, and components from conception to achieve EMC. This requires emphasis on and constant attention to EMC factors in all RDT&E projects. All DoD components shall be responsible for EMC emphasis in RDT&E of communications-electronics equipments, subsystems, and systems, and shall ensure exchange of information regarding the results of these efforts.

Concepts and Doctrine

The military departments and the Joint Chiefs of Staff are responsible for the development of concepts and doctrine that will consider EMC factors in field deployment of C-E equipments, subsystems, and systems that will minimize the impact of interference effects. This part of the program will require:

1. Analysis for EMC of all current and proposed concepts and doctrine at the earliest possible time to ensure that they will not be invalidated by degradation of sensors or communication equipment due to mutual or external interference.

2. Consideration of EMC factors in war gaming to ensure awareness of the total electromagnetic environment in the evolution of new concepts and doctrine.

The military departments shall be responsible for providing proper EMC impact consideration in the formulation of their intra-service concepts and doctrine.

Operational Problems

The objectives of the EMC Program in the operational problem area call for a capability to detect, report, solve, and correct current operational EMC problems in a time short enough to be effective. Solving operational EMC problems will require:

1. Procedures for detecting and channels for reporting electromagnetic incompatibilities that degrade combat effectiveness in the field.
2. Application of existing measurement and analysis techniques to identify the sources of the problems and determine corrective action.
3. Procedures for rapid implementation of required corrective action.

Test and Validation Area

To establish confidence in design standards and specifications and in EMC analysis and prediction efforts, field engineering test facilities are required to provide:

1. Problem parameter measurements.
2. Evaluation of EMC analyses of predictions in appropriate, real or simulated, environments.

DEPARTMENT OF THE ARMY

The Army was assigned the task of leadership in two EMC Program areas: measurement techniques and instrumentation, and test validation.

MEASUREMENT TECHNIQUES AND INSTRUMENTATION

The Secretary of the Army, or his designee, is assigned responsibility for developing and maintaining a coordinated plan stating the needs of the military departments for electromagnetic measurement techniques and instrumentation. This effort is coordinated closely with the Assistant Secretary of Defense for Installation and Logistics, with the Department of the Navy planning for standards and specifications, and with the Department of the Air Force planning for data base and analysis capability.

The Director of Defense Research and Engineering (DDR&E) or his designee for the EMC Program reviews the measurement techniques and instrumentation plan yearly in May simultaneously with the test and validation plan specified in the following subsection, and, if required, designates DoD components to proceed with development of specific items.

All DoD components cooperate in this effort and ensure that their RDT&E programs contribute to and do not duplicate the planned efforts.

TEST AND VALIDATION

The Secretary of the Army or his designee is assigned responsibility for the development of a coordinated plan for test and validation requirements in support of the DoD EMC Program. This specifies EMC Program needs for:

1. Problem parameter measurements.
2. Evaluation of EMC analyses and predictions.

The DDR&E and the Chairman, Joint Chiefs of Staff or their Designees review the plan for test and validation yearly in May simultaneously with the plan for measurement techniques and instrumentation specified in the previous subsection and if required, designate DoD components to carry out specific requirements of the plan.

DEPARTMENT OF THE AIR FORCE

The Secretary of the Air Force or his designee is assigned responsibility for developing a coordinated plan for development of EMC analysis capabilities and use of the EMC data bases. The DDR&E and the Chairman, JCS or their designees for the EMC program review the plan yearly in October, and if required, designate DoD components to carry out specific requirements of the plan. The Department of the Air Force has been designated the management agency for the Joint DoD Electromagnetic Compatibility Analysis Center (ECAC) at the U. S. Navy Marine Engineering Laboratory, Annapolis, Maryland.

DEPARTMENT OF THE NAVY

DoD EMC STANDARDS AND SPECIFICATIONS

The Secretary of the Navy or his designee is responsible for developing and maintaining a coordinated plan to provide a complete range of component, circuit, equipment, subsystem, and system EMC standards for the Department of Defense. Related standards for prediction, measurement, and validation of EMC are included. This responsibility has been assigned to Naval Electronics Systems Command (NAVELEX) by the Assistant Secretary of Defense for Installation and Logistics as an Area Assignment in accordance with DoD Directive 4120.3, "Defense Standardization Program." The status of this assignment is reviewed yearly in January by the Director of Defense Research and Engineering or his designee for compliance with the DoD EMC Program and specific direction provided, if required.

All DoD components cooperate in this preparation of specifications and standards and ensure that all C-E specifications cite appropriate EMC standards developed under the DoD EMC Program.

Where EMC standards are required but do not exist, the responsible DoD components shall take positive action through the Department of the Navy to initiate a standard. Pending issuance of a standard, each C-E specification shall contain detailed requirements which, in the opinion of the cognizant DoD component, will ensure both design and operational electromagnetic compatibility.

NAVY EMC PROGRAM

The Chief of Naval Operations is designated as the executive for the Department of the Navy in the area of electromagnetic compatibility (Figure 1). Further, the Director of Communications under the Director, Command Support Programs is assigned the responsibility for the direction and coordination of matters pertaining to electromagnetic compatibility within the Department of the Navy. The Chief of Naval Material ensures that electromagnetic compatibility is achieved in the material phases of design, development, procurement, installation, and operation of electrical/electronic equipments within the Department of the Navy.

Under the Vice Chief of Naval Operations, the Director, Tactical Electromagnetic Programs (OP-093) helps ensure that operational commanders are provided with the integrated and compatible tactical electromagnetic systems to perform their missions. The Director, functioning as a management agency of the CNO, provides for the coordination and compatibility of weapons, sensors, electronic warfare, communications, and command control subsystems of surface and air components to make these systems effective in a realistic tactical electromagnetic environment. The Director will maintain close liaison with the Director ASW Programs (OP-095) to insure coordination of efforts which overlap in time, space, and technology. In general, the Director's efforts will focus on tactical activity at and below the task force level. He will also achieve close liaison and coordination with the Director Command Support Programs (OP–094) both in establishing requirements for support at and below the task force level and assuring coordination and compatibility with support concepts and technology in areas in which OP-094 has mutual or special purview.

NAVELEX INST 5420.3 establishes a Naval Material Command EMC Executive Committee to advise and assist the Commander NAVELEX, in accomplishing the policy direction, overall program planning, guidance, coordination, and review of the Naval Material Command's EMC Program. The objective of this program is to implement those portions of the DoD EMC Program assigned to the Chief of Naval Material.

JOINT COMMAND RESPONSIBILITIES AND FUNCTIONS

The Communications-Electronics staffs of the DoD military departments respond through the MCEB to the JCS when EMC and related matters are of mutual concern. The JCS coordinates matters relating to C-E concepts and doctrine for joint operations, including EMC operational problems and joint frequency assignments.

JCS CONCEPTS AND DOCTRINE

The Chairman, Joint Chiefs of Staff, or his Designee for the EMC Program is responsible for submission of concepts and doctrine for joint operations to the ECAC for analysis of EMC impact.

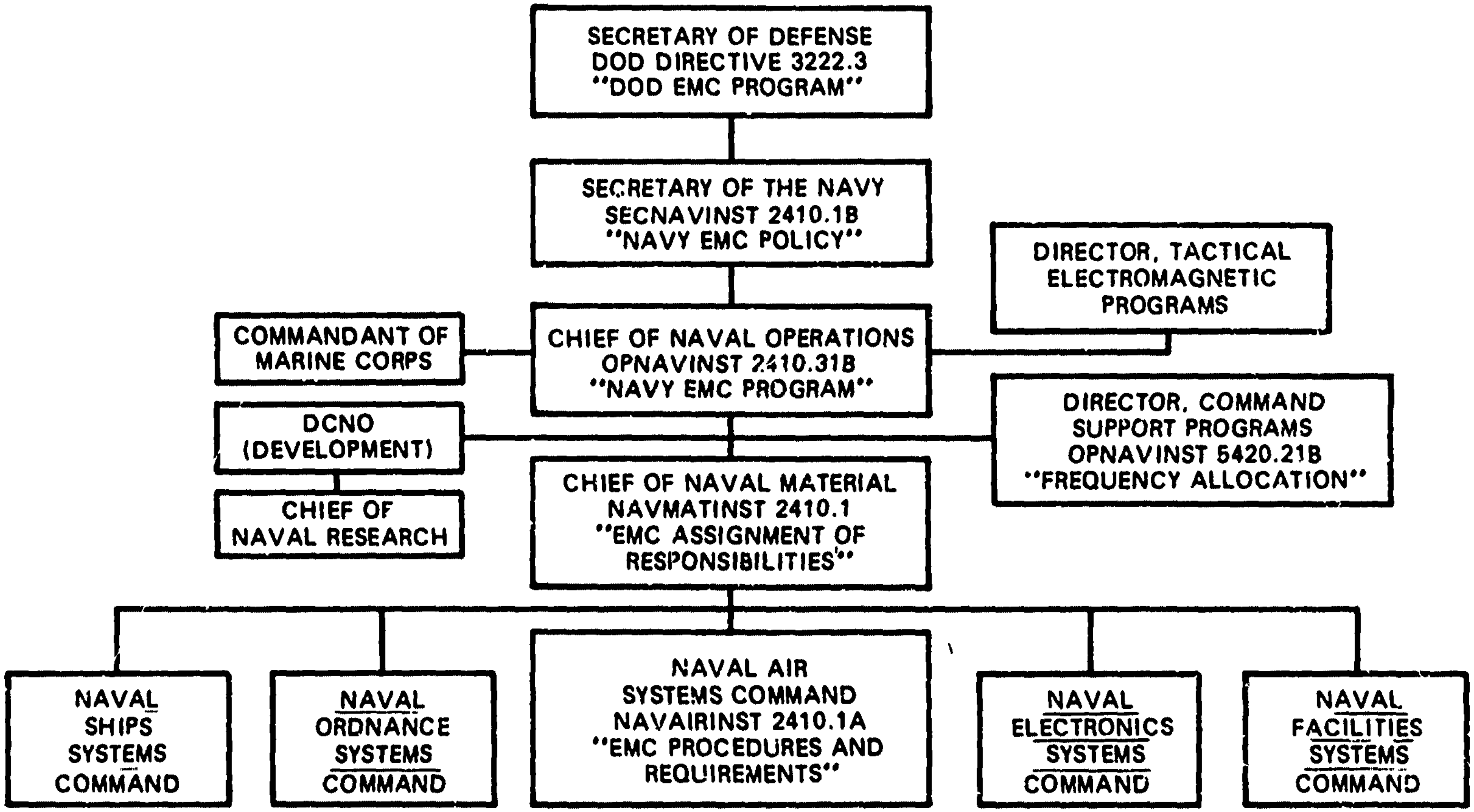

FIGURE 2-1 EMC RESPONSIBILITY WITHIN THE NAVY

JCS OPERATIONAL PROBLEMS

The Chairman, Joint Chiefs of Staff, or his Designee for the EMC Program is responsible for developing and implementing procedures and channels for detecting and reporting current joint operational EMC problems.

MILITARY COMMUNICATIONS-ELECTRONICS BOARD (MCEB)

The mission of the Military Communications-Electronics Board (MCEB) is to:

1. Coordinate military communications-electronics matters among the DoD components, between DoD and other government departments and agencies, and between DoD and representatives of foreign nations.
2. Provide DoD guidance and direction in those functional areas of military communications-electronics for which MCEB is assigned responsibility.
3. Furnish advice and assistance, as requested, on military communications-electronics matters to the Secretary of Defense, the Joint Chiefs of Staff, the military departments, and other DoD components.

Functions of MCEB include development and implementation of procedures for participation in the DoD EMC Program, as required. As a part of this function, the EMCP Designees of DDR&E and the Chairman, JCS, have tasked MC[illegible] to assist the Designees in carrying out their responsibilities for continu[illegible] surveillance of the EMCP and for providing specific direction as necessary to ensure a well-coordinated current and vigorous program and achievement of EMCP objectives.

Primary responsibility within the MCEB for EMCP matters has been delegated to the Joint Frequency Panel.

Joint Frequenc[illegible] Panel (JFP)

To evaluate the compatibility aspects of electronic equipments under conditions of operational use, as well as to conform to the national structure of frequency management, an orderly procedure for frequency management is necessary. Each DoD military department is responsible for supplying information to the Joint Frequency Panel of the Military Communications-Electronics Board (MCEB) and for enforcement of resultant decisions. When research and development is conducted under contract by private industry, it is the responsibility of the cognizant procuring activity or contracting agency to maintain sufficiently detailed surveillance of such activities to process frequency assignment applications for experimental, developmental, or operational use.

The Joint Frequency Panel (JFP) is responsible to the Military Communications-Electronics Board (MCEB) in the areas of radio propagation and frequency allocation, coordination and assignment, and in matters connected with the DoD EMC Program (EMCP). The JFP consists of a minimum of one member and an alternate from each service or agency within the composition of the MCEB. The present membership consists of Army, Navy, Air Force, Joint Staff, USMC, Coast Guard, DCA, and NSA. The JFP is responsible

to the MCEB for implementation of MCEB responsibilities for EMC matters including:

1. Review and assessment of actions being taken by the military departments in each EMCP area, advising the program Designees of noted deficiencies and actions indicated.

2. Recommendation of projects to support the development of operational plans for the enhancement of the DoD EMCP.

3. Preparation and submission to the Designees of an annual report of the status of the DoD EMCP, high-lighting progress made, areas in which increased emphasis and/or redirection is needed, and recommendations for specific actions for program enhancement.

4. Review and approval of applications for spectrum allocations for new C-E equipments and systems through the J-12 panel of the JFP.

5. Establishment and coordination of a Joint Functional Frequency Allocation Table for guidance of research and development activities.

ELECTROMAGNETIC COMPATIBILITY ANALYSIS CENTER (ECAC)

The Electromagnetic Compatibility Analysis Center, a Department of Defense facility, was established to provide advice and assistance on EMC matters to the Secretary of Defense, the Joint Chiefs of Staff, the military departments, and other DoD components. ECAC serves other Government agencies and civilian activities as resources permit. ECAC is under executive control of the DDR&E and the Chairman, Joint Chiefs of Staff or their Designees who jointly provide policy guidance, assign projects, and establish project priorities. ECAC management and administrative direction are provided by military and civil service personnel under the direction of the Secretary of the Air Force, and technical operation is provided through a contract with the Illinois Institute of Technology Research Institute.

ECAC Services

ECAC provides users with the analytical solution of EMC problems or computer print-outs from a comprehensive EMC data base containing topographical information, associative surroundings, and technical characteristics of equipment. ECAC has established an EMC analysis capability consisting of mathematical models and computer programs developed and applied by a group of engineers and analysts experienced in electromagnetic compatibility. Conclusions and recommendations are summarized in a report to the agency that submitted the project. A presentation of results is provided if desired. The following services, based on the use of ECAC analytical techniques, are typical of those available:

1. Assistance from an EMI standpoint to system developers on all aspects of frequency selection, equipment design, and placing in operation of new C-E systems.

2. Guidance in selecting locations for all types of C-E equipments.

3. Determination of power densities as affected by distance and topography.

4. Prediction of EMC degradation for various tactical missions.

5. Technical consultation to frequency management, primarily on the potential effects of incorporating new electronic systems into present and future environments.

6. Evaluation of potential equipment sites for electronic line-of-sight coverage and for compatibility with surrounding electronic and topographic environments.

Spectrum Signatures Library

One of the requirements of the EMC Program is the collection of a library of spectrum signatures of receivers as well as emitters currently in use and constantly updated as new equipment is introduced into service. The collection plan was approved for this purpose on October 28, 1960 and implementation by the DoD military department is under way.

Procedures for measuring spectrum signature characterisitcs were standardized with the issuance of MIL-STD-449, which has been modified and updated to MIL-STD-449C, 1 March 1965.

In the Army the spectrum signature measurement program is being carried out at the Army Electronic Proving Ground, Fort Huachuca, Arizona. The Air Force program is being conducted by the Rome Air Development Center, Griffiss Air Force Base, New York. The Navy is currently updating its spectrum signature collection program under the auspices of the Electronics System Command (NAVELEX).

These collection programs are contributing to the Spectrum Signature File maintained by ECAC. The file is used principally in augmenting theoretical knowledge to develop mathematical models representing C-E systems and in conjunction with solutions of specific EMC problems.

MUTUAL SERVICE RESPONSIBILITIES

EMC TRAINING

Each military department is responsible within its own organization for:

1. Ensuring that properly balanced emphasis on EMC is included in all formal courses in design, maintenance, and operation of C-E components, circuits, equipments, subsystems, and systems.

2. Maintaining current handbooks describing the most effective techniques for meeting the standards for EMC. Adoption of other adequate DoD component handbooks is encouraged.

3. Ensuring adequate participation by appropriate members of their department or agency in the symposia, conferences, and other professional activities of industry organizations and technical societies concerned with EMC.

SERVICE OPERATIONAL EMC PROBLEMS

The military departments are responsible for developing and implementing procedures and channels for detecting, reporting, solving, and correcting intra-component operational EMC problems. They provide feedback from this to the standards, design, concepts and doctrine, educational and analytical elements of the DoD EMC Program.

The DoD components cooperate in the development of data base and analysis capability and are responsible for:

1. Maintaining the ECAC data bases complete and current with regard to all equipments, subsystems, and systems developed or operated by their component.
2. Using ECAC capabilities to the maximum practical extent, rather than developing duplicates. The requirement for development of some parallel or complementary data base and analysis capability by DoD components is recognized. The need for separate data bases should decrease as communications between data processing systems improve.
3. Developing new data bases and analytical techniques when required for intra-departmental problems which, with minimum modification, may be exchanged with and used by the Joint DoD ECAC and other DoD components.

TEST AND VALIDATION SUPPORT

The military departments are responsible for the development and operation of test and validation facilities to support intra-service EMC requirements. These shall be developed to permit joint use, and shall be available to other departments when necessary. They ensure service test and operational evaluations of their equipments and systems as appropriate to ensure EMC in typical operational environments and establish confidence in analyses and predictions performed.

FREQUENCY COORDINATION

Because of critical spectrum utilization problems in connection with national and service test and training range operations, the MCEB has assigned Area Frequency Coordinators (AFC) to perform joint radio frequency coordination in these particular areas. In effect, the AFC coordinates frequency usage, minimizes harmful interference, promotes the DoD and National EMC programs, and responds to reports of interference. In the performance of these tasks, the AFC monitors and arbitrates frequency assignments and exercises control of electronic countermeasures operations in his geographical area of responsibility under authority of the Joint Chiefs of Staff.

Area Frequency Coordinators

At the present time, DoD AFC's have been established as follows:

Eastern AFC, Patrick AFB, Fla.

Sub AFC, Roosevelt Roads, P.R.

Gulf AFC, Eglin AFB, Fla.

AFC, Fort Huachuca, Ariz.

AFC, White Sands Missile Range, N.M.

Western AFC, Point Mugu, Calif.

AFC, Oahu, Hawaii

AFC, Kwajalein Missile Range, M.I.

The need for day-to-day monitoring at the test ranges is apparent. The Coordinator is responsible for interference-free conditions and is given sufficient latitude in which to make the various adjustments without the requirement for lengthy negotiations typical of needs at the national level.

The DoD Area Frequency Coordinators maintain current records of frequencies which have been coordinated for use in their areas of cognizance. They also provide advice as to probability of harmful interference which might be caused to or from proposed operations. Area Frequency Coordinators frequently arrange for time sharing and technical adjustments to minimize interference. AFC's review and evaluate all frequency allocation and assignment requests proposed for use within their area of cognizance to determine compatibility with spectrum users in their respective areas. FCC action on non-government applications for certain frequencies is coordinated with the cognizant DoD AFC. The CONUS DoD AFC's also function as Field Frequency Selection and Coordination representatives of the Office of Telecommunications Policy for specified frequency bands. AFC's assist the MCEB in the implementation of the DoD EMC Program as appropriate.

Navy Fleet/Naval District Frequency Coordination

Frequency coordination at the Fleet or District level is accomplished within the broad framework of international, joint, and intra-Navy arrangements. Frequency coordination at the Fleet Commander's and District Commandant's level is concerned with a specific geographical area and is limited to coordination of frequencies assigned for Navy use in that area. This includes:

a. Coordination of frequency use within the Fleet/District concerned.

b. Maintenance of files of frequency assignments.

c. Prevention and/or correction of harmful interference.

d. The study of frequency use as affected by propagation and the making of recommendations for changes in frequency assignments.

e. Coordination of frequencies for use of electronic systems, including TACAN, homing beacons, telemetry, DASH, fixed wing drones, radar.

Proposed uses of frequencies should be thoroughly examined prior to activation to determine interference potential. In addition, subordinates should be educated in the proper use of frequencies and prevention of harmful

interference, as well as the prompt and accurate reporting of interference when occurring so that remedial measures may be taken.

OTHER GOVERNMENT AND CIVILIAN ACTIVITIES CONCERNED WITH DoD EMC PROGRAM

Many government-industry organizations with representatives from equipment manufacturers, government agencies, operating interests, advisory activities, and universities are concerned with electromagnetic problems. Because it is obviously impossible to isolate DoD radiation or susceptibility from other occupants of the common spectrum, EMC problems are shared and the solutions are subject to consolidation. A study is now underway to find means for correlating findings of government and non-government activities engaged in EMC investigations. Records are being examined to find what data are available for EMC calculations and to provide guidance on common formats. Records in the following agencies are being studied: DCA, ECAC, FAA, FCC, GSA, OTP, JFP, NASA, Department of the Treasury, and the Weather Bureau. Various proposals have been made for establishment of a Nationwide organization similar to ECAC. One such proposal recommends establishment of a Telecommunications Research and Analysis center (TRAC) under the Department of Commerce to provide support in spectrum management and other matters leading to improved utilization of the radio resource.

Figure 2-2 illustrates U. S. Government dual control of the frequency spectrum. The figure shows the dual nature of control, with separate functions falling under executive and legislative branches. The frequency spectrum is a natural resource under sovereign domain, and in time of emergency the President may authorize any use of any portion of the spectrum as he may deem fitting – as may the head of any other government for forces under his control. For purposes of EMC, JTAC is a non-government activity that has acceded to a Federal Government request to act as a focal point for technical studies and for formulation of objectives for spectrum management.

JOINT TECHNICAL ADVISORY COUNCIL (JTAC)

JTAC is a joint committee of the Institute of Electrical and Electronics Engineers (IEEE) and the Electronic Industries Association (EIA) set up to assist the FCC and other government agencies to find solutions for difficult problems in radio and electronics. JTAC Subcommittee 63.1 on Electromagnetic Compatibility addresses its efforts to three distinct tasks:

1. To identify present EMI problems and existing control techniques.
2. To establish technical approaches toward solving and controlling compatibility problems and toward developing greater efficiency in the use of the radio spectrum.
3. To recommend technical procedures that would increase effective and efficient use of the radio spectrum.

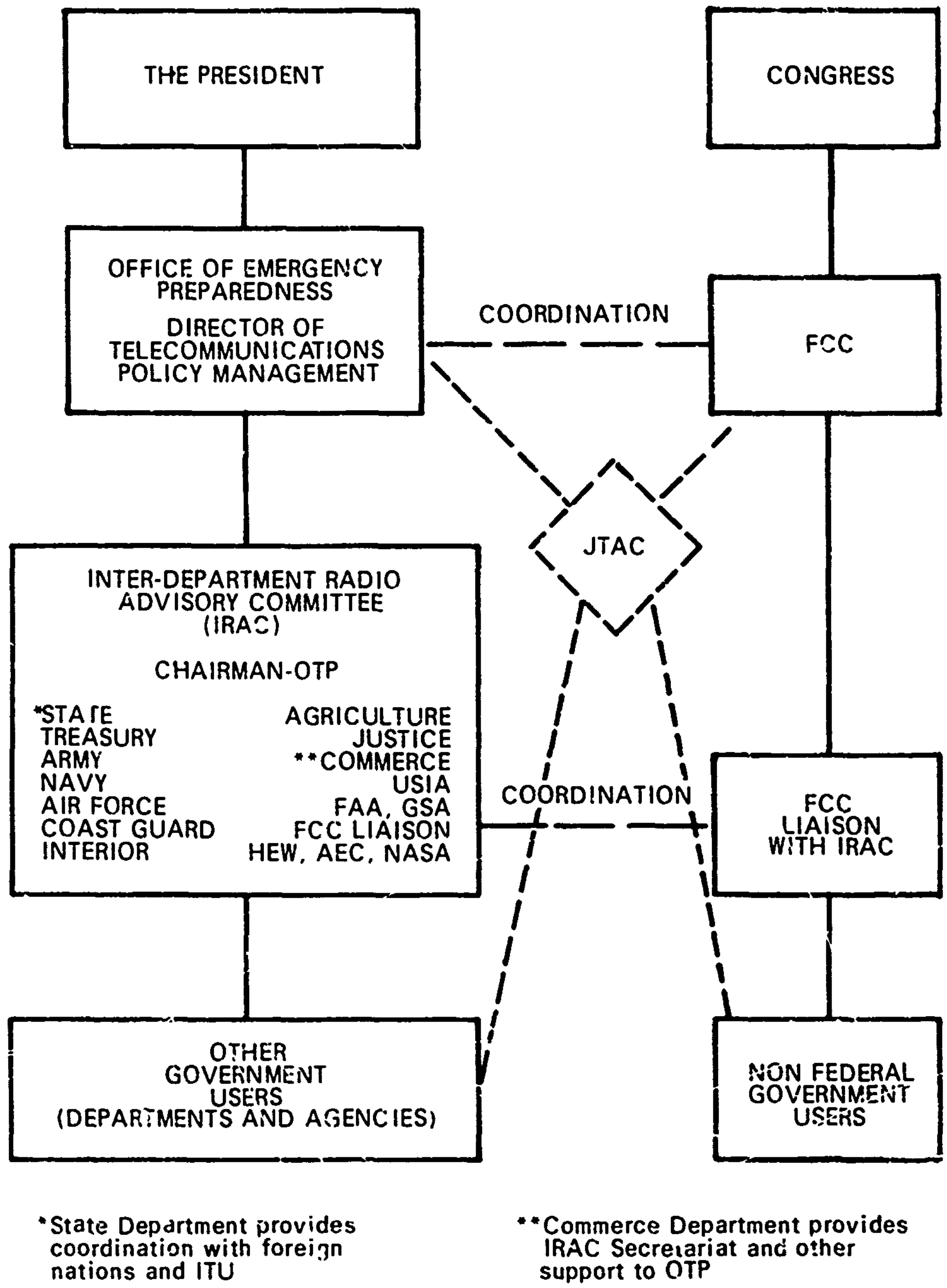

FIGURE 2-2 U.S. DUAL CONTROL OF THE FREQUENCY SPECTRUM

FEDERAL COMMUNICATIONS COMMISSION (FCC)

FCC interference regulations are designed to protect all U. S. users of the electromagnetic spectrum. FCC regulatory and licensing powers are derived from the Congress of the United States and extend to non-Federal Government users of the spectrum. Recent amendment of the Communications Act of 1934 (by addition of Section 302 in July, 1968) has applied restrictions to the manufacture and sale as well as to the use of devices capable of interference. Before this amendment, FCC authority was limited to injunctions against the use of such devices after they had been placed in operation. Enforcement of this new portion of the Act is still incomplete, and many devices manufactured before its enactment remain in use. However, users who have encountered trouble following the purchase of incompatible equipments such as plastics formers and garage door openers, have learned to look to the FCC for equipment authorizations. The FCC has two classes of authorizations: equipment-type approval based upon tests made in FCC laboratories, and equipment-type acceptance based upon presentations and test data furnished by manufacturers. Some equipments also require certification by a qualified engineer that the equipment, as it is installed, meets FCC standards as to levels of undesired conducted and radiated energy. Neither authorization nor certification shall be construed as a license to operate the device.

To ascertain that licensed devices are operating on their designated frequency and in accordance with regulations, and that unlicensed emitters are not causing interference, the FCC operates 18 monitoring stations equipped with direction finders so that unknown interference sources can be located by triangulation. When FCC measurement of frequency or other characteristics of a device shows that it is operating in an unauthorized manner, or an unlicensed device is radiating harmful interference, the offender is located and notified to correct the condition.

In addition to domestic monitoring service and the FCC monitoring stations, 15 other monitoring stations operated by RCA, Mackay, and others participate in the International Monitoring Service. This agency gathers spectrum occupancy data from the 33 U. S. monitoring stations and sends it to the International Frequency Registration Board of the International Telecommunications Union for use in frequency allocation studies.

Although the FCC is not a member of IRAC, it provides liaison representation and offers cooperation in all matters of mutual interest.

OFFICE OF TELECOMMUNICATIONS POLICY (OTP)

The Director of Telecommunications Policy (DTP) in the Executive Office of the President acts with the advice and assistance of the Interdepartment Radio Advisory Committee (IRAC) to authorize use of the electromagnetic spectrum for activities under the jurisdiction of the U. S. Government. IRAC is the common focal point for all government activities on matters concerning spectrum management, although the DoD components have an alternative path to the OTP through the Secretary of Defense. Statistics collected by the OTP

include lists of frequency assignments made to Government activities by the OTP/IRAC system. In the event of a national emergency, all frequency resources, both civil and military, would be administered by the Director, Office of Telecommunications Policy under the overall policy direction and planning assumptions of the Director, Office of Emergency Preparedness.

FEDERAL AVIATION ADMINISTRATION (FAA)

The FAA is involved in electromagnetic compatibility of communications and navigation facilities associated with aeronautical services. FAA Airways Traffic Control systems must be compatible with military systems serving a similar or identical function, not only from the mutual electromagnetic interference point of view, but also that of commonality of airspace communication and navigation facilities. The FAA renders service to military aircraft as well as to civil aircraft. For example, the ATC radar beacon system (ATCRBS) used by the FAA is the same as the military Mode 3 IFF/SIF, using the same frequencies, IFF interrogation codes, and SIF reply codes. Likewise, portions of the FAA VORTAC facility is congruous with the military TACAN-DME system. To accommodate military aircraft, FAA operates a dual air-ground communication system; 225-400 MHz for the military, 118-136 MHz for all others. Military ground stations participate in ATC activities and many radars perform dual ATC-air defense functions.

The FAA is the largest user of the radiated electromagnetic spectrum among the government agencies, except for the Department of Defense. With but few exceptions, FAA uses of the spectrum are an integral part of the Air Traffic Control (ATC) system, which is directly related to flight safety. Airspace use is rising rapidly, with consequent increase in the use of ATC facilities. The airspace and the ATC facilities are shared by military, commercial, and general aviation, and their EMC problems are interrelated. The increase in aviation-related activity, not all of which involves the FAA, has also brought about an increase in radio services and EMC problems on the part of the Weather Bureau, which is a major user of the spectrum, and commercial air carriers who employ company communications, airborne weather and doppler radar, and radio altimeters.

The Frequency Management Division of the FAA Systems Research and Development Service is engaged in EMC investigations which will be of benefit to the DoD EMC Program. The increase of electromagnetic emitters operating close together in geography and spectrum produces a multitude of intermodulation problems which are under consideration by the FAA Frequency Management Division. The FAA has monitoring and field measurement equipment in mobile units and in aircraft to investigate particular problems. EMC determinations of the FAA Frequency Management Divison are presented as recommendations to IRAC, which in turn submi .ts evaluation and findings to DTM. In addition, FAA has submitted a large number of entries to ECAC data files on environment, geographical, and equipment characteristics, and uses ECAC print-out data on its planning. ECAC is also making an EMC analysis on ATC problems for the FAA on a contract basis.

AERONAUTICAL RADIO INCORPORATED (ARINC)

ARINC is a corporation wholly owned by the commercial airline companies. The purpose of ARINC is to provide consulting, planning, engineering, and operational C-E support to the airlines. As the chief consultant of the airlines, ARINC has participated in almost every national and international body which manages the use of the radio spectrum. ARINC manages spectrum use of two types of radio stations: their own and those owned by the airlines. ARINC ties into the worldwide Aeronautical Fixed Telecommunications Network and provides both Airways Traffic Control and airline company communications. ARINC coordinates equipment standards and frequency management matters with the FCC, and with IRAC through the FAA.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA)

The National Aeronautics and Space Administration has unique demand upon the radio frequency spectrum in its role of peaceful exploration of space. NASA's use of the spectrum is not extensive, but reliable communications on which the lives of astronauts depend, are of prime importance. Because of the strict reliability requirements, and because of the distances involved in communication, telemetry, and control links, NASA has made extensive investigations into EMC matters. NASA publication NHB 5320.3 "Electromagnetic Compatibility Principles and Practices," prepared as part of the Apollo Program, outlines the EMC technical standards and specifications for electronic components. This publication has provided the guidelines for contractors who supply material to NASA and DoD procurement activities.

INSTITUTE FOR TELECOMMUNICATIONS SCIENCE (ITS)

The Department of Commerce operates the Institute of Telecommunications Science (ITS). ITS representation to IRAC is through the Department of Commerce. ITS performs atmospheric and ionospheric investigations relating to influences of refractive index and attenuation upon radio wave propagation. These effects, of course, affect the field intensity of a signal at points remote from its source. ITS also investigates geomagnetic, auroral, and solar effects upon radio propagation. Below 60 MHz, ionospheric effects are of primary concern; above 60 MHz the effects of surface ducting and tropospheric scatter predominate. Information relating to wave propagation and changes in field intensity at points located some distance from the transmitter or source of interference is an integral part of frequency management. Of interest to the military concepts and doctrine area of the DoD EMC Program is the influence of surface trapping or ducting upon UHF/SHF emission. Ducting conditions can extend the surface detection and tracking range of a radar far beyond the normal horizon distances normally attributed to the radar, while the radar detection range of an aircraft flying just above the duct will be reduced by the "beam split effect." Height finding accuracy will also be degraded. Furthermore, a UHF circuit or microwave link thought to be tactically secure because of frequency may be heard with clarity at a great distance because of

waveguide modes of propagation in an atmospheric duct.

Diurnal, seasonal, and sun spot cycle variations of wanted and unwanted signals will affect frequency channel assignments, while "sudden ionospheric disturbances" and "sporadic-E conditions" affect circuit reliability. The findings and RF propagation predictions of ITS are published in a series of bulletins by the Government Printing Office. In addition, ionospheric propagation disturbances notices are transmitted by WWV and WWVH at 45 minutes past each hour.

Weather Bureau

Another large-scale government user of the electromagnetic spectrum is the Weather Bureau, which operates extensive weather radar, radiosonde, weather satellite, and communications networks. Collection of weather data is coordinated with DoD, Coast Guard, and NASA facilities, with dissemination of data to a vast number of activities, of which the principal ones are the military and FAA. In fact, most Weather Bureau field stations are collocated with FAA facilities at airports. EMC problems involving Air Defense and FAA radars are common, as are problems involving communications links on which the Weather Bureau operates. EMC findings and recommendations may be reported to IRAC via Department of Commerce representation.

ARMED FORCES COMMUNICATIONS AND ELECTRONICS ASSOCIATION (AFCEA)

The communications arms of each of the armed forces are represented with vice presidents on the Executive Agency of the Board of Directors of AFCEA. The monthly journal, "Signal," contains articles of EMC and related subjects by military and civilian members. The annual convention, usually held in May or June; is also a source of information of EMC through panel discussions and formal papers. The contact point for AFCEA is:

Armed Forces Communications and Electronics Association
1725 Eye Street, N.W.
Washington, D.C. 20006

SOCIETY OF AUTOMOTIVE ENGINEERS (SAE)

The SAE has an extensive technical effort in support of aerospace systems and equipments. Committee AE-4, which deals with electromagnetic compatibility, has about 25 projects to develop EMC reports for industry. The committee is organized so that the participants do not represent their own organizations, thus enabling the best technical recommendations to be developed. The contact for the SAE committee on EMC is:

SAE Committee AE-4
Society of Automotive Engineers Inc.
Two Pennsylvania Avenue
New York, NY 10001 (Phone 212-594-5700)

ELECTRONICS INDUSTRIES ASSOCIATION (EIA)

Committee G-46 of Electronics Industries Association also has a number of EMC projects. This committee is organized with participants representing their own organizations in order to obtain an industry viewpoint. Some of the G-46 projects are Designers Guide, EMI Films, Evaluation Measurement Techniques, Systems Effectiveness, System Power Quality, FCC EMI Controls, and EMI Requirements for Commercial Equipment. This committee can be contacted at:

Committee G-46
Electronic Industries Association
2001 Eye Street, N.W.
Washington, D.C. 20006

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (IEEE)

The IEEE group on EMC (G-EMC) sponsors an annual symposium usually held in June, July, or August, and it also periodically publishes various EMC proceedings and transactions. Active chapters of G-EMC exist in many metropolitan centers and military installations where chapter meetings are held periodically. In addition, the G-EMC organizes EMC sessions at the IEEE International Convention and at regional conferences. The G-EMC Transactions, published quarterly, contains papers, short notes, and correspondence on EMC related subjects. A G-EMC newsletter is published bimonthly, on an alternate schedule with the G-EMC Abstracts of current publications. The interest of G-EMC is in frequency management, computer analyses, and origins, effects controls and measurements of EMI. The contact point is:

Institute of Electrical and Electronics Engineers
345 East 47th Street
New York, NY 10017

The IEEE is a joint sponsor, with the EIA, of the Joint Technical Advisory Commission (JTAC). JTAC, ever since its formation in 1948, has been dedicated to the improved use of the electromagnetic spectrum in the national and international interest. In this connection, it has made studies and published reports on spectrum utilization and spectrum engineering.

NATIONAL FIRE PROTECTION ASSOCIATION (NFPA)

The NFPA has developed a number of standards that directly involve EMC although the term EMC is not used by the NFPA. The NFPA documents and standards make an important contribution to EMC, lightning protection, HERO and RADHAZ and a number of the NFPA documents have been accepted as United States of America Standards. Among the more important NFPA publications which affect EMC are:

NFPA STD	SHORT TITLE	USA STD
70-1968	National Electrical Code	C1-1968

77-1966	Static Electricity	
78-1968	Lightning Protection	C5.1-1968
325M-1965	Flammable Liquids, Gasses, Solids, Fire Hazard Properties	
407-1968	Aircraft Fuel Servicing	z119.1-1968
495-1967	Explosives and Blasting Agents	

The NFPA may be contacted at the following address:

National Fire Protective Association
60 Batterymarch Street
Boston, Mass. 02110

MILITARY EMC FACILITIES

ARMY FACILITIES

Electromagnetic Environmental Test Facility (EMETF)
U. S. Army Electronic Proving Ground, Fort Huachuca, Arizona

TECHNICAL AREAS: Electronic and Electrical Engineering, Computer Science.

DESCRIPTION: The EMETF is the Army's major facility for accomplishing EMC test, analysis, and validation. It uses four interrelated activities to accomplish its tasks: An Interference Prediction Model (IPM), Field Facility (FF), Instrumented Workshop (IWS), and Systems Scoring Facility (SSF). Together, they form a comprehensive facility to test and evaluate equipments, systems, and operator performance for solving problems concerned with radio frequency interference, compatibility, and vulnerability.

Electromagnetic Interference Control Test Facility
Fort Monmouth, New Jersey

TECHNICAL AREAS: Electronic and Electrical Engineering.

DESCRIPTION: The facility contains instrumentation for implementing interference emission and susceptibility testing over the electromagnetic spectrum in the frequency range of 10 Hz to 40 GHz. Work benches for the design and fabrication of component test setups are provided. Fixed and mobile shielded enclosures are also available for conducting interference emission measurements in a controlled electromagnetic environment when high ambient conditions exist. Additional shelter for housing test instrumentation encompasses a macadam surface which provides adequate area for radiated susceptibility measurements. The facility is fully equipped to perform and analyze all the interference characteristics of the latest electronic equipment in accordance with specification MIL-E-55301 (EL) and MIL-STD 461,462, and 463.

Electromagnetic (RFI) Test Laboratory
Aberdeen Proving Ground, Maryland

TECHNICAL AREAS: Electronic and Electrical Engineering

DESCRIPTION: This laboratory is capable of measuring and recording conducted and radiated frequency interference (RFI) and field intensity (FI). This facility also includes the capability of conducting antenna pattern measurements and ambient surveys, and of analyzing frequency spectrum signatures.

Electromagnetic Interference Test Facility
Fort Monmouth, New Jersey

TECHNICAL AREAS: Electronic and Electrical Engineering; Laboratories, Test Facilities, and Test Equipment.

DESCRIPTION: This facility makes it possible to conduct the following investigations: electromagnetic radiation from electronic and electric systems, susceptibility of electronic and electric systems to electromagnetic radiation. The enclosure is capable of performing tests required by MIL-STD-461, 462. (Electromagnetic Interference Measurements and Interference Control Requirements.) As a result of these tests, interference control measures can be incorporated and tested without interference to operating equipments in the area. All power lines, 60 Hz, 400 Hz and DC, are filtered upon entering the enclosure. The enclosure is air conditioned so that tests may be conducted without interruption due to climatic conditions.

Electromagnetic Radiation Effects Test Facility
White Sands Missile Range, New Mexico

TECHNICAL AREAS: Laboratories, Test Facilities, and Test Equipment.

DESCRIPTION: The prime mission of the facility is to analyze the effects of high intensity radio frequency environments on Army material. The aspects involved are disclosure of potential hazards and effects on reliability. The facility provides high intensity (200 volts/meter) electromagnetic fields at radio frequencies from 1 kHz through 10.5 GHz. This is the only facility in the U. S. capable of generating these high field intensities and covering an RF spectrum of this width. The size of the test specimen which can be accommodated is unlimited. Specialized instrumentation of the test specimen and measurement of the test environment is also provided by the facility including data acquisition, data reduction, analysis and technical reporting.

Spectrum Signature Facilities
U. S. Army Electronic Proving Ground
Fort Huachuca, Arizona

TECHNICAL AREAS: Electronic and Electrical Engineering

DESCRIPTION: The Spectrum Signature Complex consists of an instrumented fixed facility and mobile facilities of three fully instrumented

self-powered measurement vans used for electrical characteristics measurements specified in MIL-STD-449. These facilities are used for determining desired and undesired radiation characteristics of all types of U. S. Army communications-electronic equipment and for implementing electronic studies and experiments of an exploratory research nature to obtain further knowledge of basic phenomena and causes affecting electromagnetic compatibility.

NAVY FACILITIES

Naval Air Test Center
Patuxent River, Maryland

TECHNICAL AREAS: Test, evaluation, BIS trials, and rework of aircraft.

DESCRIPTION: Responsibility for EMC work at NATC is in the Communications Engineering Branch of Weapons Systems Test Division. The Electromagnetic Interference (EMI) Section is presently using the Interference Test Laboratory to conduct tests of aircraft/weapons systems for compliance with MIL-E-6051. Expertise and specialized equipment are available for TEMPEST nonstop testing of airborne secure communications systems. In addition to the Interference Test Laboratory, a solid copper shielded room, 9-1/2 feet by 15 feet and several portable screen rooms are available. Radio frequency interference (RFI) test and measurement instrumentation is available to conduct tests to MIL-STD-462. There is also the capability to measure spectrum signatures and make EM site surveys.

The Weapons System Test (WST) division at NATC includes a laboratory building complex with a large screened hangar, shielded cubicles, laboratory spaces, and test equipment installations arranged around the hangar space. Test control areas are established in modular cubicles or vans positioned in areas either ancillary or internal to the main structure. Office, storeroom, service, and utility areas are integrated into the structure contiguous to the hangar. This complex was designed and constructed primarily to provide a large excluded area comparatively isolated from incursions of extraneous electromagnetic energy from outside sources.

The entire hangar area is sheathed inside a structural shell with galvanized iron hardware cloth laid onto steel and wood frames. Screening under the floor is doubled. There are external weather doors that roll back to unmask an additional set of screened doors. Openings and apertures are bonded by use of finger stock and other techniques. Special power facilities are shielded and installed contiguous to the complex as a source of regulated power for electrical, electronic, and utility service systems used during test operations. Power for internal connection to aircraft under test is distributed through filtered elements into the screened area to floor level service pits recessed into the hardstand. Services for compressed air, hydraulics, and refrigerated air may be rolled in on trailers or dollies.

Within the structure and outside the screened hangar there are five laboratory areas. Each of these laboratories includes a double-shielded room.

These spaces have regulated and filtered power for bench testing equipment, with or without environment control.

Planning is presently underway to provide Naval Air Systems Command with electromagnetic compatibility lead laboratory capability. NATC will be tasked to study and plan for expanded facilities, instrumentation, and personnel to provide the lead laboratory capability necessary to implement the Naval Air System Command's EMC responsibility.

U. S. Naval Weapons Laboratory
Dahlgren, Virginia

TECHNICAL AREAS: Test and evaluation of Naval Ordnance Systems.

DESCRIPTION: The EMC effort at NWL Dahlgren is distributed along broad task lines and incorporates nearly all of the electromagnetic compatibility requirement. The EMC measurement facilities at NWL Dahlgren are currently devoted to three basic work areas. The following paragraphs briefly describe these areas and their progress.

Measurement Techniques and Instrumentation. Development of measurement methods, techniques, procedures, and equipments to permit valid determination of the composite electromagnetic environment pertinent to the design of ordnance systems, in order to insure adequacy of electromagnetic performance. This work includes development of receiving and recording devices to permit rapid and accurate definition of complex, uncontrolled electromagnetic environments.

EM Interference Control Evaluation Techniques. Development of methods, techniques, and procedures for valid determination of electromagnetic interference (EMI) functional responses in individual ordnance equipment or subsystems.

Spectrum Signature Measurement Techniques. Development of measurement models, procedures, and equipments to permit determination of electromagnetic signature characteristics of electronic countermeasure systems.

Naval Civil Engineering Laboratory (NCEL)
Port Hueneme, California

TECHNICAL AREAS: Nuclear electromagnetic pulse (NEMP) studies of protective measures and detectors. Power line filter measurement techniques under operational conditions.

DESCRIPTION: The laboratory is equipped with radio frequency interference receivers, CW, random and impulse sources covering the frequency range of 60 Hz to 10 GHz. There is a capability for measuring insertion loss and voltage attenuation of 60 Hz and 400 Hz power line filters loaded at up to 400 amperes. Signal levels of several amperes can be injected with current probes in a range of 100 Hz to 2 MHz. Electromagnetic site surveys and spectrum signatures can be performed in conjunction with related development efforts such as the NCEL interference-attenuating power conductor.

Naval Electronic Laboratory (NELC)
NELC System Test Facility XAVT-9
San Diego, California

TECHNICAL AREAS: Spectrum surveys of the RF environment, both external to the hull and internal to the communication spaces. Analysis of the total communications systems behavior including secure communications systems.

DESCRIPTION: Measurement equipment to automatically plot spectrum surveys from 14 kHz to 1 GHz. Two shielded rooms are installed on the hangar deck of the CVAN-68 that is used as a test bed. The EMC capability of the facility is used only as needed, and therefore is not in use 100 percent of the time.

Naval Electronic Laboratory Center (NELC)
NELC Equipments Effectiveness Division
San Diego, California

TECHNICAL AREAS: EMI testing of components and equipments with limited capability in the area of system testing; evaluation of EMI properties of shipboard electronic equipments against requirements of equipment specifications. Closed-system emission spectrum signature capability exists, with present instrumentation extending from 14 kHz to 10,000 MHz in narrowband equipments and from 50 kHz to 40 GHz in broadband spectrum analyzers.

DESCRIPTION: EMC measuring facilities include two double electrically isolated screen rooms in adjacent locations.

Field intensity meters cover the range of 14 Hz to 10 GHz. Standard signal generators are available for narrowband signals from 5 kHz to 11 GHz, and a Stoddart Model 91263-1 impulse generator provides a source for broadband signals. A Hewlett-Packard 851B/8551B spectrum analyzer permits broadband emission spectrum signature measurements.

EMC measurements within the Equipments Effectiveness Division are usually performed in the course of complete engineering evaluations of equipments.

U. S. Naval Applied Science Laboratory (NASL)
Brooklyn, New York

TECHNICAL AREAS: EMC effort is devoted to measurement techniques; instrumentation design, construction, and evaluation; and EMI testing of equipments or systems to military specifications or standards.

DESCRIPTION: The EMI facility at NASL consists of a complete equipment complement required to perform measurements in accordance with MIL-I-16910C and MIL-STDs-461, 462, 463.

Metrology Engineering Center (MEC)
Naval Ordnance Systems Command
Naval Plant Representative
General Dynamics Pomona Division
Pomona, California

TECHNICAL AREAS: EMC test instrumentation and calibration.

DESCRIPTION: The Engineering Division, Electronic Branch of MEC is responsible for EMC measurements in the Navy Calibration Program. The task is performed by the frequency, time, and field intensity group. Certain items are also scheduled into other available laboratories such as General Dynamics Pomona Division, for environmental tests, etc. Such tests are usually for evaluation purposes when calibration programs require knowledge of electromagnetic compatibility of new standards and test equipment.

U. S. Naval Research Laboratory (NRL)
Washington, D. C.

DESCRIPTION: *Radio Antenna Branch, Code 5450 (Radio Division)*: In connection with the development of multicouplers, an effort is being made to determine the effects of intermodulation on the compatibility of components and circuit designs in the presence of strong electromagnetic fields. Complete instrumentation is available for such measurements over the 2 to 400 MHz frequency range. No increase in this activity is being planned. Mobile antenna facilities now being designed in this branch could readily be used for EMC measurements. Basically, measurements of antenna performance, site surveys, and EMC involve identical instrumentation. These several mobile facilities will operate in major parts of the frequency spectrum between 2 and 10,000 MHz.

Radio Communication Systems Branch, Code 5410 (Radio Division): Four commercial shielded rooms are available, three of which are located in security vault spaces. Spectrum analyzers and signal generators are on hand for measurements from LF through UHF. There are no EMC measurements being performed or planned in this branch.

Electromagnetic Materials Branch, Code 5220 (Electronics Division): Work in this branch on absorbent materials for radio waves has proved helpful on various occasions in problems concerning RFI, EMC, and radiation hazards to personnel. However, it does not have specific programs, or special equipment, for use on any of these problems.

Naval Avionics Facility (NAFI)
Indianapolis, Indiana

DESCRIPTION: EMC FACILITIES – One screen room with limited capability is currently being used to conduct electromagnetic interference tests. This enclosure is designed to provide shielding required by the latest existing EMC/EMI test specifications including the low audio frequencies as well as the higher microwave frequencies. The enclosure additionally provides a wide variety

of built-in filtered feed-through circuits and removable sub-panels that can be adapted for testing the effectiveness of shielding materials and devices, and cables and connectors. These sub-panels also provide for testing insertion loss of filters which cannot be tested using MIL–STD-220A test fixture. Necessary instrumentation to support one shielded enclosure over the 20 Hz to 40 Hz frequency range is available. The shielded enclosure and instrumentation provides for testing in accord with military specifications and standards.

AVAILABILITY OF FACILITIES – The facilities described above have been procured primarily to support research, development, and pilot production programs at this facility and to support certain pre-production test programs relative to contractor-produced avionics equipment for the Naval Air Systems Command and the Aviation Supply Office. It is expected that the available facilities will be used at full capacity in support of these existing programs.

Naval Ship Engineering Center, Norfolk Division
(NAVSEC NORVA)
Norfolk, Virginia

DESCRIPTION: The facility, staffed by qualified EMC engineers, contains two instrumented vans capable of making measurements in the frequency range of 14 kHz to 40 GHz, plus a screen room. The vans have self-contained power sources, and one has a shielding effectiveness of 100 db in the frequency range of 100 MHz to 40 GHz. Measurements that can be made include spectrum signature, EM ambient levels, antenna patterns, and limited MIL-STD-461 measurements.

U. S. Navy Underwater Sound Laboratory (USNUSL)
Fort Trumbull, New London, Connecticut 06321

DESCRIPTION: A major government laboratory facility with a broad range of measurement and testing capabilities. In EMC studies, particular emphasis has been in the frequency range of 1 Hz to 100 kHz. Measurements included EM environments, cable coupling, magnetic shielding, grounding and bonding, and EM propagation through sea water.

Naval Electronic Systems Test and Evaluation Facility
(NESTEF)
Patuxent River, Maryland 20670

TECHNICAL AREAS: Laboratories, field test facilities, and test equipment.

DESCRIPTION: NESTEF is the primary EMC laboratory for the Naval Electronic Systems Command. It is committed to measurement of spectrum signature, performance of technical investigations in support of the ECAC, and site survey investigation.

The physical portion of NESTEF devoted to EMC consists of two fixed laboratories, two mobile laboratories, and field facilities for propagation and

antenna pattern measurement. The EMC effort is also supported by the Instrumentation Divison of NESTEF which evaluates EMC equipments and performs measurements to MIL-STD-462.

The EMC division maintains a state-of-the-art instrumentation inventory to perform all measurements to MIL-STD-449 ( ) from 30 Hz to 26.5 GHz. Both laboratory and field measurements of spectrum signatures are made.

AIR FORCE FACILITIES

Electromagnetic Interference Facility
Wright-Patterson AFB, Ohio

DESCRIPTION: A laboratory having the capability of performing electromagnetic measurements, conducted and radiated, in the frequency ranges of 50 Hz to 15 kHz and 0.15 MHz to 10 GHz. Primarily used to evaluate measurement techniques and limits for military design standards and specifications. It is also used to evaluate shielding effectiveness of shielded cables and materials, suppression devices, and filters.

MAJOR EQUIPMENT: Screen room (ACE, 10' x 16' x 8'); spectrum plotter (White, 120A); microwave field intensity meter (Empire devices, NF-105); radio interference and field intensity meters (Stoddart NM-10A, NM-20B, NM-30, NM-50); spectrum analyzer (Hewlett-Packard).

Electromagnetic Test Facility
Wright-Patterson AFB, Ohio

TECHNICAL AREAS: Electronic instrumentation, flight test instrumentation, microwave radiators, reflection patterns, grid-type structures, microwave reflection, propagation tests.

DESCRIPTION: This facility consists of a laboratory equipped with work benches, hand tools, some power tools, and standard commercial and military electronic instrumentation consisting of frequency generating, receiving, and measuring equipment. It is used as an engineering tool in concept development, communications techniques development, and investigation and validation of circuits and communication equipment from 10 kHz to 400 MHz. The facility includes an anechoic room for conducting microwave reflection and propagation tests over short distances in the 8 to 12 MHz frequency range.

Electromagnetic Compatibility Laboratory
Wright-Patterson AFB, Ohio

TECHNICAL AREAS: RF bonding and shielding, spectrum signatures, circuit susceptibility, electromagnetic interference, RFI antenna.

DESCRIPTION: This facility provides for the investigation of aerospace RFI reduction techniques by exploring techniques for measuring and controlling electromagnetic interference that is internal and external to the flight vehicle. The characteristics of interference sources, receptor vulnerability, and the

coupling path between them are analyzed. Investigations include bonding, shielding, spectrum signature, microelectronic solid-state circuit susceptibility, transient interference studies, antenna or probe development and evaluation, and electromagnetic hazards.

Antenna Proving Range
Newport, New York

TECHNICAL AREAS: Antenna performance measurement.

DESCRIPTION: This facility consists of four antenna ranges in an essentially interference free area used to measure antenna performance parameters, +0.25 dB side lobes over 40 to 60 dB dynamic range, 1° to 50° beamwidths $\pm$ 0.01°, gain measurements using calibrated standard gain horns, and VSWR using precision slotted lines.

Electromagnetic Test Facility
Verona, New York

TECHNICAL AREAS: Electromagnetic radiation, optical detection, radar detection, biological-RF radiation, direction finding, ECCM simulation.

DESCRIPTION: This facility consists of eight laboratory buildings, nine power stations, a headquarters building, two butler buildings — one specially shielded for RFI measurements and research, four arctic towers, and a supply building. The facility supports engineering evaluation and operational testing of ECCM, radio frequency interference reduction techniques, radar, communications, millimeter wave research, optical surveillance techniques, and electromagnetic vulnerability testing. The facility also provides special instrumentation for spectrum signature, QFIRC and special instrument techniques tests, and precise spatial positioning of test aircraft.

Electromagnetic Test Facility (Airborne)
Griffiss AFB, New York

TECHNICAL AREAS: Aircraft instrumentation, antenna pattern measurements, electromagnetic detection, wave propagation, radio frequency density measurements, programmed aircraft flight control.

DESCRIPTION: This facility provides for the instrumentation, maintenance, and operation of airborne ECM systems and radio frequency recording equipment. One specially equipped C-131 aircraft contains an AN/FSM-17 antenna pattern analyzer with a capability to record fundamental, spurious and harmonic frequencies generated by a ground emitter. Three C-131 aircraft and one KC-135 aircraft are equipped to record ground-emitted HF radio frequencies. One C-131, one KC-135, and four M-109 vans can be instrumented with various ECM configurations.

coupling path between them are analyzed. Investigations include bonding, shielding, spectrum signature, microelectronic solid-state circuit susceptibility, transient interference studies, antenna or probe development and evaluation, and electromagnetic hazards.

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Ground Electronics Engineering Installation Agency (GEEIA)

Five organizational GEEIA regions span the globe. They are the Air Force Logistic Command's Eastern GEEIA, at Keesler AFB, Miss., Western GEEIA at McClellan AFB, Calif., Central GEEIA at Tinker AFB, Okla., Pacific GEEIA at Wheeler AFB, Hawaii, and European GEEIA at Wiesbaden AFB, Germany. Headquarters, GEEIA is at Griffis AFB, New York.

TECHNICAL AREAS: To analyze, identify, and correct electromagnetic interference problems world wide on operational AF ground electromagnetic equipment, or to provide advice and assistance to the Air Force or others, as directed, on electromagnetic interference aspects of equipment during conceptual, development, acquisition, and siting phases. A quick reaction capability is needed world wide to analyze and correct electromagnetic compatibility problems, and to provide ready siting information (interference prediction and prevention) on proposed electromagnetic equipment and deployments, no matter how much forethought goes into equipment design and deployment.

DESCRIPTION: Special task forces are detached as necessary to remote areas. For example, a task force from Pacific GEEIA is stationed in Vietnam to conduct tests, analyses, correction, and validation during the war there. Meanwhile, short term task forces from Central GEEIA, and HQ, GEEIA, conducted field surveys, path loss measurements at and between Air Force sites and Sentinel (Safeguard) sites in the Fall of 1968 and in the Spring of 1969. Data was used to determine Air Force constraints on the Safeguard system or necessary fixes to Air Force equipment and to refine prior rough estimates on interference potential.

REFERENCES

1. *DoD Directive 3222.3 of July 5, 1967, Department of Defense Electromagnetic Compatibility Program*

2. *Tenth Tri-Service Conference on Electromagnetic Compatibility, IEEE Proceedings, 1968.*

3. *Department of Defense Electromagnetic Compatibility Analysis Center, ECAC-DAS-1-69.*

4. *Department of the Navy Frequency Management Handbook, DNC-25A.*

5. *OPNAV Instruction 5400.29 of 9 August 1967, Radio Frequency Coordination Procedure for Use at National and Service Test and Training Ranges and Downrange Sites.*

6. *AFSC DH 1-4 Electromagnetic Compatibility Design Handbook.*

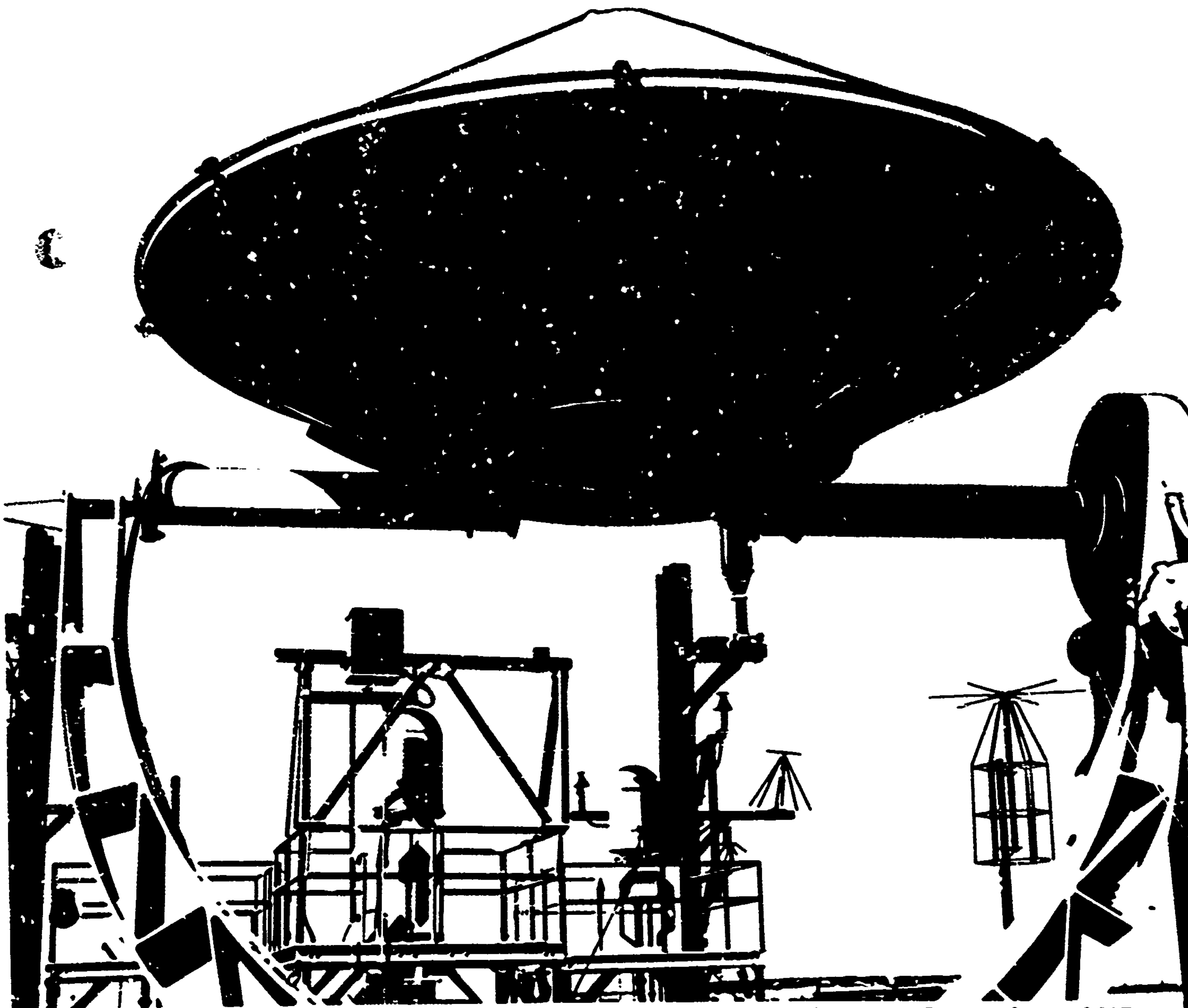
7. *Department of Defense Electromagnetic Compatibility Program - Test and Validation Plan CY 1969.*

NAVAIR 5335

NAVAL AIR SYSTEMS COMMAND

ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 3



PUBLISHED BY DIRECTION OF COMMANDER, NAVAL AIR SYSTEMS COMMAND

CHAPTER 3
THE NAVY PLANNING SYSTEM

CONTENTS

ILLUSTRATIONS

PLANNING SYSTEM DOCUMENTS

The ever-increasing use of communications-electronics (C-E) equipment for military command and control and as parts of weapon and data systems, has generated certain problems. Among these is electromagnetic compatibility (EMC). Electromagnetic compatibility is the capability of C-E devices to operate at designed levels of performance without degradation due to interference. Although much has been done in recent years, C-E equipments being delivered to operating forces of the Navy still do not always fit into the total weapon system in a compatible manner.

Because of the size of problems involving military electronic equipments and the way in which they are used, EMC requirements must enter the planning and budgeting programs of the Navy early. Problems involving EMC become increasingly severe with the advent of aerospace technology on an operational basis. Documents comprising the Navy planning system are therefore being strengthened to provide the necessary policy guidance.

The Department of Defense Programming System is the normal process by which program decisions are made regarding force levels, weapon systems, and support programs of the defense establishment. The DoD EMC Program which set forth EMC policy and objectives was initiated by a SECDEF Memorandum in 1960. Previous SECNAV guidance emphasized the need for increasing EMC effort and provided policy direction within the Navy. By DoD Directive 3222.3 of 5 July 1967, the DoD EMC Program has been revised, upgraded, and given specific direction to provide for an integrated DoD effort with extended objectives in the eight specified EMC Program areas discussed in Chapter 2.

EMC considerations and procedures are applicable throughout the Navy in research, planning, design, development, procurement, production, maintenance, and operation of all C-E equipments and electrical devices which may be sources of, or susceptible to, electromagnetic energy.

Two facets of EMC must be considered in the early stages of planning. (1) Operational compatibility planning based on clear concepts and doctrine must go through the frequency management agencies so that each proposed project can be fitted into the electromagnetic spectrum without disrupting or being disrupted by other activities. (2) Design compatibility planning based upon the resultant frequency allocation or assignment can then follow to ensure that the hardware produced develops no troublesome susceptibility or harmful interference outputs.

THE NAVY PLANNING SYSTEM CONCEPT

The Navy Planning System provides for development of Navy plans and associated programs for direct inputs into, and service consideration of, DoD plans. The Navy Planning System is responsible to, and operates within, the Joint Program for Planning. OPNAV Instruction 5000.19E, "The Navy Planning and Programming System," sets forth the basic Navy planning documents, describes the relationship between the various plans, and assigns responsibilities for their preparation, review, and updating.

The Navy Planning System serves three basic purposes:

(1) It provides for the development of Navy concepts, requirements, and objectives, and for their convincing presentation to higher authority in order to introduce the viewpoint of the Navy into Joint strategic plans, the DoD planning system, and Navy program planning which resolves annually into the budget submitted by the Navy to the Secretary of Defense.

(2) It provides for the translation of strategic and operational concepts, technological and intelligence forecasts, and guidance received from higher authority into research and development, force level, personnel and support plans and objectives.

(3) It provides guidance and direction for the application of current capabilities.

The various plans and documents of the Navy Planning System interact in such a way that they constitute an integrated system. The output of some of the plans constitute a major part of the inputs to others in order to provide overall integration and coherence.

RELATIONSHIP OF NAVY PLANS TO JOINT PLANS

The Navy Planning System is designed to be responsive to the Joint Program for Planning of the Joint Chiefs of Staff, the Department of Defense Programming System, and the Congressional budget cycle. There is a two-way relationship between the Navy Planning System and the Joint Program for Planning. The Navy Planning System provides inputs into the Joint Planning System, and Navy plans implement Joint plans.

Joint Program for Planning

The Joint Chiefs of Staff have approved a Joint Program for Planning (JCS Memorandum of Policy No. 84) which provides annually for one Joint Long Range Strategic Study (JLRSS), two Joint Strategic Objectives Plans (JSOP), a Joint Intelligence Estimate for Planning (JIEP), and a Joint Research and Development Objectives Document (JRDOD). It is from these documents that statements of military requirements are developed.

Joint Long-Range Strategic Study (JLRSS)

The JLRSS is the long-range plan which states the view of the Joint Chiefs of Staff concerning use of U. S. military power. It provides broad strategic

guidance for the development of military policies, plans, programs, and research and development objectives. The effective planning period is for ten years subsequent to the Base Date, which is always 1 July of the current year

Joint Strategic Objectives Plan (JSOP)

The JSOP provides the principal military advice of the Joint Chiefs of Staff to the Secretary of Defense for development of the DoD budget, and provides planning guidance to commanders of unified and specified commands and services for the mid-range period. It is the basic military document against which continuing military recommendations and actions on force levels and related issues concerning strategy can be measured. For the purposes of the JSOP, the mid-range period begins two years following the Base Date and extends for eight years thereafter.

Joint Research and Development Objectives Document (JRDOD)

The JRDOD supports the JLRSS and JSOP by (1) translating broad strategic guidance concerning operational requirements into the research and development objectives essential to support the strategic concept, and (2) providing advice to the Secretary of Defense regarding the relative military importance of research and development effort essential to support strategic concepts, military objectives, and the needs of commanders of unified and specified commands.

Joint Intelligence Estimate for Planning (JIEP)

The JIEP provides a principal intelligence basis for the development of the JLRSS, JSOP, and JSCP. It is prepared by the Director, Defense Intelligence Agency and submitted to the Joint Chiefs of Staff for approval.

Joint Strategic Capabilities Plan (JSCP)

The JSCP provides a statement of military strategy to support national policies and objectives based on capabilities and extends for one year (effective 1 July of the current fiscal year). The JSCP constitutes a planning directive to commanders of unified and specified commands for the execution of military tasks assigned.

DOCUMENTS OF THE NAVY PLANNING SYSTEM

The six basic documents of the Navy Planning System discussed below constitute the Navy portion of DoD planning and are used as a basis for RDT&E planning and programming. Other documents of the Navy Planning and Programming System, and additional information on the ones discussed here, can be found in OPNAV Instruction 5000 19.

Navy Strategic Study (NSS)

The NSS states the concepts and philosophy concerning future naval contributions to national defense and provides basic guidance for Navy long-range and mid-range planning. It appraises the world situation for these periods, outlines the potential threats, and the U. S. policy, objectives, and strategy. It summarizes the Navy's role and tasks and provides a scientific and technological forecast. The NSS, with annexes described in the following two paragraphs, is issued on 1 January and covers five to twenty years from the end of the current fiscal year.

Navy Mid-Range Guidance (NMRG)

The NMRG, Annex A to NSS, projects qualitative force and research and development guidance for five years beginning 1 July, five years after the end of the fiscal year in which it is approved. It provides a basis for the development of research and development goals, and with the basic document it provides a basis for the Navy input to the JSOP strategy and mid-range strategy guidance used in the development of the Mid-Range Objectives (MRO).

Navy Long-Range Guidance (NLRG)

The NLRG, Annex B to the NSS, provides the long-range research and development guidance for ten years beginning 1 July, ten years after the end of the fiscal year in which it is approved. The NLRG is the primary basis for the Navy input to the JLRSS and JRDOD. It provides a broad frame of reference for mid-range planning and, with the basic document, provides long-range strategic guidance used in the development of the MRO.

Mid-Range Objectives (MRO)

The MRO serves the dual purpose of deriving the quantitative force structure goals and of advancing new concepts and technology by providing guidance for updating operational requirements and advanced development objectives. The force structure goals are for the eleventh fiscal year after that in which they are approved. They provide guidance for initial Navy force objective inputs to JSOF and for initial PO (Navy Program Objectives) forces, together with broad supporting rationale. MRO force goals express the requirements to execute foreseeable Navy tasks efficiently and with a reasonably high expectancy of success. The MRO also presents tentative projections of desirable changes toward new or radically revised systems which may be additions to, or replacements for, units within the basic force goals for the year stated. The purpose of these projections is to stimulate analytical and development action which will make possible the introduction in later force goals of specific units with the new capabilities desired.

Department of the Navy Program Objectives (PO)

The PO is a statement of Navy force level objectives approved by the Secretary of the Navy, projected eight years beginning two years after the fiscal year in which it is approved. It projects the resource levels of personnel, procurement, research and development, and supporting programs for five years. It represents the level to which the Secretary of the Navy supports the objectives established by the Chief of Naval Operations (CNO) and the Commandant of the Marine Corps (CMC) in the JSOP. It is updated as required, at least annually. The Program Objectives are addressed in the Navy Programming Manual (OPNAV 90P-1C).

Department of the Navy Five-Year Program (DNFYP)

The DNFYP is the Navy portion of the DoD Five-Year Defense Program (FYDP) approved by the Secretary of Defense. It covers funding for all Navy programs of prior, current, and succeeding five fiscal years, and projected force levels for an additional three years. Program funding is in accordance with the ten DoD numbered programs discussed more fully later in this chapter.

The DNFYP is updated monthly, and summaries are distributed at least twice a year and at other times as the Secretary of Defense may direct, or as the Director, Navy Department Program Information Center, may deem essential. Minor updates are normally issued monthly to reflect decisions made during the previous month.

RESEARCH, DEVELOPMENT, TEST, AND EVALUATION (RDT&E) PLANNING PROCEDURES

The basic inputs into the research and development planning system come from the Navy Long-Range Strategic Study and Joint Long-Range Strategic Study. Long-range planning for RDT&E is concerned with establishing goals for the future and with developing optimum means for their achievement. The kind of long-range planning required in RDT&E does not attempt to freeze future systems into a design perceived today, but rather to provide for the things which must be done today to develop and preserve the options needed to meet the uncertainties of tomorrow.

SOME CHARACTERISTICS OF THE RDT&E PLANNING PROCESS

RDT&E planning within the Navy is characteristically conducted as a dialogue between the user interest (Fleet Operating Forces) and the producer interest (Naval Material Command). The planning dialogue between the user and the producer is conducted within the framework of the management doctrine set forth in paragraph 12 of General Order Five, "Assignment and Distribution of Authority and Responsibility for the Administration of the Department of the Navy." This paragraph reflects three important characteristics of the RDT&E planning process: the "contract" nature of the relationship between the user

interest and the producer interest, the necessity of choice to provide optimum military worth from limited resources, and the importance of information flow.

The Contract Nature of User-Producer Relationship

The relationship between the user interest represented by the Chief of Naval Operations (CNO) and the Commandant of the Marine Corps (CMC) as spokesmen for the Operating Forces, and the producer interest represented by the Chief of Naval Material (CNM) speaking for the Naval Material Command, is more analogous to the relationship between cooperating independent business organizations than traditional military relationships. Plans are the result of "negotiation" between the two interests. Trade-offs are made through this process which will result in the maximum capability for the Operating Forces possible within the limits of resources available to the Naval Establishment.

Resources available to the Navy are always limited. Scientific and technical resources are even more limited than general economic resources. A decision to allocate technical and scientific manpower to one line of effort automatically precludes their application toward any alternative goal. Choices will be better made when the alternatives are explicitly arrayed and selection is made deliberately.

Importance of Unrestricted Information Flow

The needs of the user must be known to producer organizations in the Navy, to the scientific community, to industry, and to all who may provide solutions. New potential or actual capabilities evolving from advancing knowledge and technology must be known to users who may be able to make use of such capabilities. Every RDT&E manager, user, and producer must be aware of alternatives open to him before he can make the choices which provide the greatest return in military worth for resources expended.

Influence of Uncertainty

Uncertainty is one of the most important influences on the RDT&E management process. The long-term future is inherently uncertain and projections of military requirements are based on assumptions subject to change.

Uncertainty and RDT&E costs are inversely related. Uncertainty is greatest at the research end of the RDT&E program where costs are least. Costs are greatest for operational systems development, the culmination of the RDT&E process. Under current policy, all major uncertainties concerning technical feasibility, military worth, and cost must be eliminated before a project can be approved for development for service use.

FORMAL STRUCTURE OF RDT&E PLANNING

A formal structure and set of procedures have been established for Navy RDT&E planning. OPNAV Instruction 3900.8 identifies the principal

requirements and planning documents and explains interrelationships between them. The several research and development programs are funded under the DoD Program VI funding structure of the Department of the Navy Five-Year Program (DNFYP).

Figure 3-1 illustrates in a simplified way the formal structure of RDT&E planning for the Navy. The principal research, development, and operational requirements papers are shown, together with the flow pattern for processing them from DoD approval through to award of a contract.

The RDT&E planning process encompasses both the user's statements of operational requirements and the producer's statement of plans for fulfilling requirements. In these formalized exchanges, the user (CNO) sets forth the capability required and the producer (CNM or other cognizant developing activity) responds with technical and financial plans for achieving the required capability.

OPNAVINST 2410.11 (series) sets forth the requirements and procedures for development of electromagnetic equipments and systems. Information requested by this directive should be furnished as early as possible so that an effective evaluation of the compatibility of the electronic equipments under anticipated operational conditions can be made, and so that EMC guidance may be provided to the developing activity. The Naval Material Command will not provide funds for development or procurement of electronic equipment designed to emit or receive radio frequencies until a frequency allocation clearance has been approved by the Office of Chief of Naval Operations (OP-094). To achieve EMC, the following items must be among those considered:

(1) The design parameters of C-E equipment
(2) Interfaces with other equipments and systems
(3) The operating environment
(4) Ability to support other systems
(5) Availability of frequency assignment
(6) Schedule of EMC tests
(7) Compliance with EMC standards
(8) Hazards of electromagnetic radiation to ordnance (HERO).

OPNAVINST 10550.12 (series) promulgates policy pertaining to reduction of interference to electronic equipment, and assigns responsibility therefor. This directive requires that:

(1) All electronic equipment design agencies consider the elimination or reduction of interference among electronic equipments as a basic requirement.

(2) All operational requirements for equipments undergoing development include a statement of requirements for control of interference.

(3) Engineering tests and technical evaluation of newly developed equipments or of systems employing newly developed equipments to determine that design requirements for interference control have been met.

(4) The operational evaluation shall provide for determining in its operational environment the susceptibility of electronic equipment to interference, the interference produced by the equipment, and any degradation of other associated equipments or systems which may result.

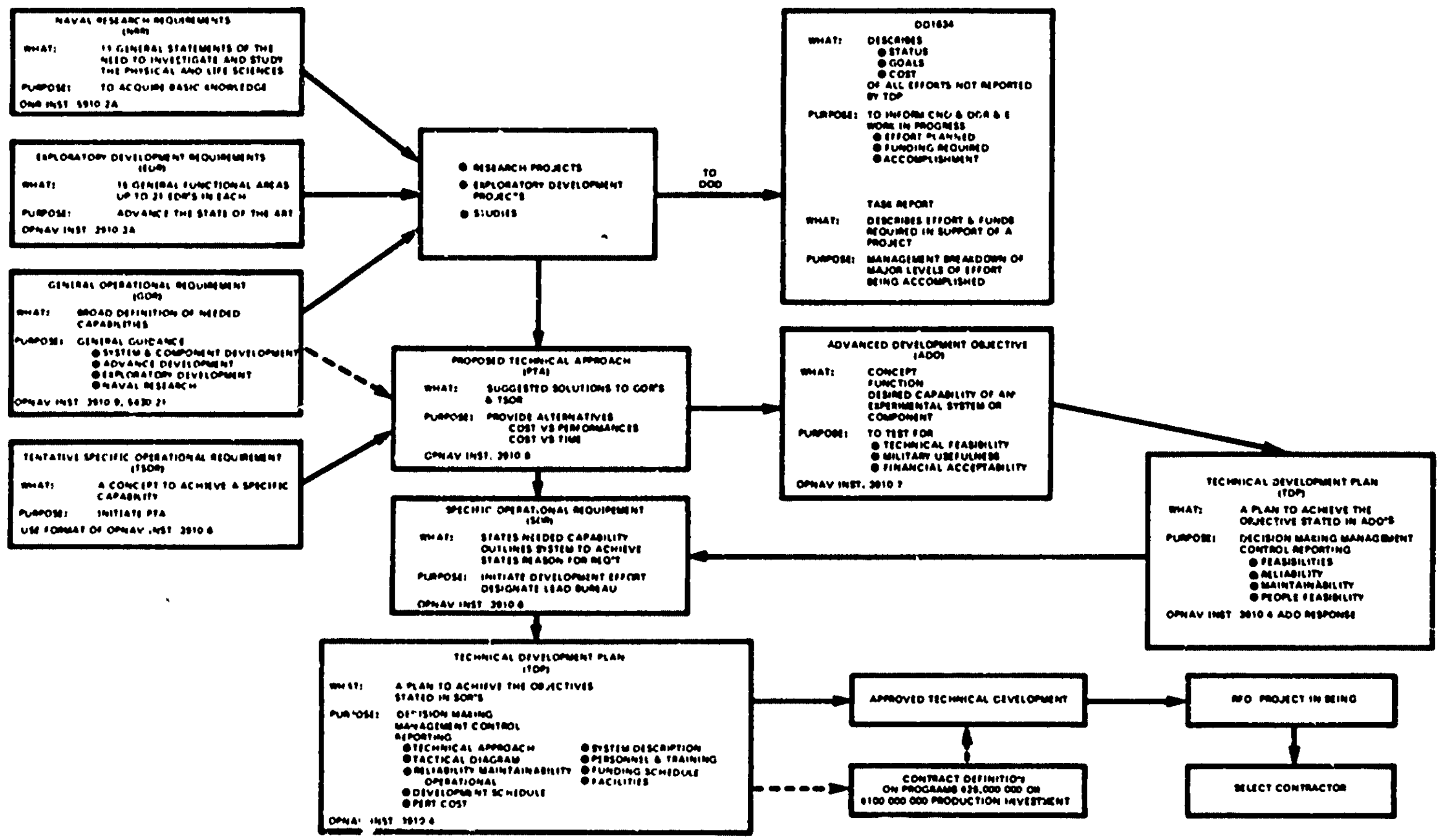


FIGURE 3-1 FORMAL STRUCTURE OF RDT&E PLANNING

OPNAVINST 10551.3 (series) promulgates and requires the inclusion of the minimum radar engineering design objectives as a part of all research and development contracts for radar systems designed to operate below 40 GHz. Compliance with the minimum radar engineering design objectives is necessary for efficient use of frequency bands allocated for radar use in an effort to provide maximum interference-free operations.

To be prepared for consideration for spectrum allocation policy and engineering matters, including electromagnetic compatibility within the system and with other users of the spectrum, RDT&E planning documents are reviewed by the Frequency Management Department of the Office of CNO. Such reviews continue through the development of Specific Operational Requirements (SOR's), Proposed Technical Approaches (PTA's), and Technical Development Plans (TDP's). Planning and Material Offices are advised of any adverse elements noted, and recommendations are made concerning compatibility. Difficult or controversial items are studied and resolved by the Frequency Allocation Advisory Board (FAAB), the principal frequency coordinating body within the Navy.

Naval Research Requirement (NRR)

A Naval Research Requirement (NRR) is a general statement of the need for investigations and studies in the physical and life sciences to solve specific practical problems and to obtain a fuller knowledge or understanding of the subject under study. The Chief of Naval Research publishes Naval Research Requirements in ONR Instruction 3910.2A. This instruction constitutes a directive to all developing agencies to plan for and initiate appropriate projects in their areas of competence and responsibility. Electromagnetic compatibility appears under item R008, "Electronic Sciences."

Exploratory Development Requirement (EDR)

Exploratory Development Requirements are promulgated by the Chief of Naval Development. Exploratory development requirements are currently set forth in NAVMAT Instruction 3910.4 with a list of planning areas for EDR's. EDR's are classified according to functional military capabilities and when aggregated, encompass the total effort directed toward improvement and expansion of naval technology.

EMC forms a part of EDR's under several classifications. Exploratory development includes all effort directed toward the solution of specific military problems, short of major development projects. This type of effort may vary from fairly fundamental applied research to quite sophisticated breadboard hardware, study, programming, and planning. It would thus include studies, investigations, and minor development. The dominant characteristic of this category of effort is that it is pointed toward a specific military problem such as EMC, with a view toward developing and evaluating the feasibility and practicality of proposed solutions and determining their parameters.

The Navy's exploratory development program develops the technology to solve specific Navy and Marine Corps problems. The program includes concept formulation in the form of analytical and experimental effort to help identify problems, determine alternate solutions, and demonstrate technical feasibility of those solutions to a degree which warrants their consideration for support under advanced development. It also includes analytical and experimental work on technologies directly related to materials, components, processes, techniques, and individual equipments of the Navy and Marine Corps. Along with research efforts, exploratory developments form the pool of technical knowledge from which weapons will be devised and developed.

EDR's establish the groups under which exploratory development will be classified for programming. Developing agencies organize EDR's into appropriate projects and tasks pertinent to their areas of responsibility.

NAVMAT Instruction 3910.7 promulgates planning procedures to facilitate coordination of the Navy's Exploratory Development Program by the Chief of Naval Development. These planning procedures require a task area report and a tentative funding profile, along with relevance codes to assist in planning, reviewing, and justification of the program.

General Operational Requirement (GOR)

A GOR is a broad statement of objectives and goals for operational capabilities needed in a major warfare or support area to meet the estimated threat of the next 5 to 15 years. A GOR states the efforts and the area being considered and provides guidance to the developing agencies for the planning and formulation of:

(1) Naval Research Programs
(2) Exploratory Development Programs
(3) Proposed Technical Approaches

Although various sources of information are used in developing GOR's, the Navy Strategic Study is the primary foundation for the statements of needed operational capabilities.

Under the general guidance of the GOR, research and exploratory effort is focused on the most pressing needs. System Commands are encouraged to submit development proposals to CNO in the form of Proposed Technical Approaches (PTA's) toward fulfilling the operational needs stated or implied in the GOR.

Mission success criteria should be established in the GOR, which, for combat aircraft systems, depend heavily upon electronic warfare capability. Achievement of this capability in turn delineates EMC requirements. The geographical and physical environment in which the forces involved are expected to operate must be considered. The GOR should stipulate the particular effects of environmental factors that may prevent or hinder the attainment of objectives. The effect of environmental factors upon the required capabilities should also be anticipated.

For guidance in making trade-offs leading to selection of weapon design, the GOR contains information on the relative importance of various capabilities

desired. GOR's also contain as much information as possible on the operational concept. OPNAV Instruction 3910.9 (series) "General Operational Requirements (GOR's) for Navy Research and Development" provides basic guidance.

Exploratory Development Goals (EDG)

Exploratory Development Goals (EDG's) are quantitative goals for exploratory development, which would provide the technical means to satisfy operational requirements for future weapons and support systems. They are based on GOR's, long-range and mid-range planning documents, and predicted threats. These quantitative goals do not constitute limits but they do establish critical levels, which, if not met, are expected to result in operational deficiencies.

It is at the exploratory development stage that the military potential of new knowledge is investigated. An EDG states a technological goal toward which investigations and studies can be applied to demonstrate new techniques or the feasibility of a system, subsystem, or component from which a new, improved, or expanded naval capability could evolve. EDG's are determined by the assessment of the capabilities needed to meet future requirements with projected forces, strategy, and tactics. Consideration is also given in this assessment to new knowledge available for exploitation. EDG's are prepared by the Chief of Naval Development.

Tentative Specific Operational Requirement (TSOR)

The TSOR is a requirement document originated by CNO and addressed to Chief of Naval Material or, if appropriate, to activities outside the Naval Material Support Organization. The TSOR amplifies details regarding a particular operational capability need which was stated in general terms in the GOR. The TSOR is an official request by the CNO for certain information required to explain the scope of effort and resources necessary to achieve a particular capability. Promulgation of a TSOR by CNO does not establish a firm Navy requirement nor does it authorize the commencement of a new development program. The TSOR states a tentative requirement for a particular capability, identifies the anticipated or existing threat, defines those performance and operational characteristic envelopes which can be specified, and indicates when the capability is needed. The TSOR also provides an estimate of the numbers of systems required.

The TSOR is a step toward defining a system, its characteristics, its deployment, and its procurement, operation, and maintenance costs. It is a means for comparing the effectiveness of a proposed system with alternate methods of accomplishing similar missions. Response to the TSOR is in the form of a Proposed Technical Approach (PTA). TSOR's will be prepared in accord with enclosure (1) to OPNAVINST 3910.6.

Proposed Technical Approach (PTA)

The PTA is a document prepared for submission to CNO by the Naval Material Command or other activity of the Navy, outlining technical approaches by which a particular capability may be achieved. This document may be submitted either as an unsolicited response to a General Operational Requirement to call attention to possibilities for a naval warfare system resulting from advanced technology, or as a solicited response to a TSOR in which alternate approaches to a capability are presented.

Almost all technical approaches to operational requirements involve complex electrical or electronic subsystems which emit or are susceptible to electromagnetic fields. The PTA should contain EMC provisions for control of these extrinsic fields which can produce electromagnetic incompatibilities, limit system effectiveness, or jeopardize the success or survivability of the proposed system.

The PTA provides CNO with technical information on which to base a decision for further development, and contains cost versus time, and cost versus performance trade-offs for the technical approaches presented. An appraisal of the technical risk involved for the several approaches and a technical appraisal of reliability, operability, maintainability, electromagnetic compatibility and support requirements of systems being considered are also included in the PTA.

The PTA should state any problems of compatibility which must be resolved in arriving at a decision to proceed with the proposed development, citing governing directives where applicable. It should also include an analysis of the communication requirements, both direct and indirect, resulting from the proposed system and alternatives. The analysis should include estimated additional communication traffic and special requirements such as unusual bandwidth, information mode or rate, and frequencies. Any requirements for communication security techniques or equipment must be included.

The PTA serves four needs in providing the best possible military posture from limited resources:

(1) It provides a formal means by which new technology is introduced into naval warfare systems.

(2) It presents to CNO certain technical and fiscal information including an estimate of the degree of risk and potential EMI problems, on which to base a decision to start a development program.

(3) It provides technical and fiscal information necessary for preparation of an SOR or ADO if appropriate.

(4) It provides the initial estimates of development and production costs in order to determine whether a formal Contract Definition will be required.

OPNAV Instruction 3910.8 (series) provides guidance for the preparation, review, and implementation of PTA's.

Advanced Development Objectives (ADO)

An ADO is a requirement document issued by user interests stating a need to conduct studies, tests, and experimental efforts whose military usefulness,

technical feasibility, and financial acceptability are not assured. Such a development may be a step in the transition from exploratory development to engineering development, or it may be for the express purpose of developing hardware for test and experimentation. The primary function of the ADO is to provide decision-making information as to whether to pursue the potential development through engineering development toward evaluation for fleet use. Information gained as a result of this effort is of great assistance in preparing the SOR.

Advanced development includes all projects that have been moved into the development of hardware for experimental or operational test. A further characteristic is that the design of such items is directed toward hardware for test or experimentation rather than expressly for eventual service use. It therefore provides a means for investigating EMC requirements and technology.

Advanced development is in the realm of design and other technical feasibility studies, and of prototype studies leading to determination of relative costs of new design versus existing design modification. EMC considerations should be included in these studies. Advanced development is usually handled by the in-house laboratories of the Naval Systems Commands and by contract with industrial laboratories. In the Systems Command laboratories, funding is by allotment from the parent organization. Some ADO projects are contracted to educational, nonprofit, or industrial organizations.

In major developments requiring Contract Definition (CD), the ADO may precede the SOR to eliminate high-risk areas and achieve more accurate cost estimates. In rare instances, CD may be required for ADO projects for which engineering development has not been considered. Here the ADO-TDP dialogue together with the TSOR-PTA inputs, if applicable, must provide the necessary information to document the prerequisites of CD. Deputy CNO for Development is responsible for establishing Advanced Development Objectives, in consultation with the cognizant DCNO, CNM, and the Director, Long-Range Objectives Group. Guidance for preparation of ADO's is contained in OPNAV Instruction 3910.7 (series.)

Specific Operational Requirements (SOR)

The Specific Operational Requirement (SOR), issued in the user interest by CNO or CMC, states a need for a particular capability and outlines the system characteristics that describe what capability is to be achieved. The SOR defines the capability in terms of mission requirements, operational concept, and performance constraints, and establishes goals for reliability, maintainability, compatibility, and personnel requirements.

The SOR results from the TSOR-PTA dialogue if the exchange indicates that there are no unacceptable risks and that technology for the system under consideration is at hand. The SOR is the final stage in the requirements documentation, and therefore must contain definitive guidance for developing a Technical Development Plan (TDP).

The decision to promulgate an SOR is a key decision in the development process. An SOR should not be promulgated unless the user organization is

firmly convinced of the validity of the operational requirement, and firmly intends to sponsor development if a suitable TDP is forthcoming.

A decision to promulgate an SOR must be made in full appreciation of the realities spelled out in General Order 5, that selection of the work to be done includes curtailment or cancellation of work already in progress in favor of work which offers greater promise or work of greater military worth. The transition from research to systems development is the promulgation of the SOR.

The SOR must provide the producer with all the information he needs to make the trade-offs involved in developing an optimum system. It must be very explicit concerning the job the user wants the system to do, the way the system is to be used, the environment under which it will operate, and the other weapons and systems with which it will be associated. The operational concept must cover not only performance but also reliability, maintainability, compatibility, and personnel requirements.

Technical Development Plan (TDP)

The Naval Material Command response to either the SOR or the ADO is a Technical Development Plan (TDP). The TDP is a plan for fulfillment of the requisites of the ADO or SOR. It is a complete and detailed description of the effort necessary for the development, together with a recommended funding schedule. Approval by CNO constitutes concurrence with technical matters described therein and authority to begin a development project, commensurate with funds provided by separate action. When funded, the TDP becomes the primary management control and reporting document for the life of the development. As such, it must be continually updated. When authorized by DDR&E a DD Form 1634 may be submitted instead of a TDP.

The TDP is the primary management document for projects in advanced development, engineering development, and operational systems development. Several of the plans which form the sections of the TDP, such as management, subsystem and system characteristics, and tests and evaluation, should specify EMC technical or administrative requirements. The TDP is revised whenever significant changes in program status occur. Though they are technically not reports, updated TDP's must be submitted on specific occasions and at stated times covered in DoD Instruction 3200.6 (SECNAV Instruction 3900.14) and OPNAV Instruction 3910.4. Updated TDP's must be submitted:

(1) When a program change is approved.

(2) Whenever a significant change occurs in the status of the project.

(3) At least once a year by 15 February to provide current information for use in reviewing project listings.

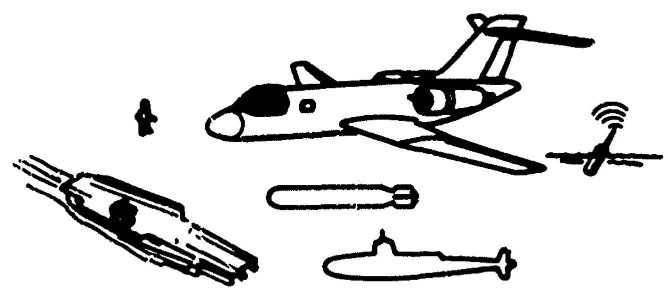
The TDP Summary, OPNAV Form 3910-3, and the TDP, serve as a concise summary of TDP information of most significance to top management. See Figures 3-2 and 3-3 for an example of a TDP Summary. It identifies a project, its subprojects, resource expenditures planned, milestones, and the reliability summary for the project. The Monthly Project Evaluation is plotted against the planning data in the TDP Summary to measure project progress.

T.D.P. SUMMARY (Page 2.1)
OPNAV FORM 3910-3

1. IDENTIFICATION AND PICTURE

Program Element 6.42.xx.xx.2

31-09 ADVANCED CARRIER-BASED ASW AIR WEAPON SYSTEM S-4(X)



CLASSIFICATION STAMP

2. DESCRIPTIVE HIGHLIGHTS

Missions: Task force and convoy screening and attack; antisubmarine barrier surveillance and attack; SOSUS contact investigation and attack; ocean surveillance; aerial mining; surface attack.

Type: Twin turbofan engines; four-man crew; automated sensor data processing.

Characteristics:

Range (max) ------------- 3500 nautical miles
Cruise speed ------------ 380 knots (max range)
Continuous speed -------- 470 knots (max)
Endurance at sea level ------------- 8 hours
Mission payload --------- 7800 pounds
Military load ----------- 14,000 pounds
Take-off gross weight ---------------- 42,000 pounds (max)

3. MAJOR SUB-SYSTEMS	FY 70	FY 71	FY 72	FY 73	FY 74	FY 75	FY 76	FY 77
Airframe	CF; Contract Definition		Design	Test Article Fab.	NPE Contr. Flt. Test	BIS	Operation	
Propulsion	Adv. Dev. 2 Contrs.	Design & Development Through PFAT		MQT	NPE	BIS	Operation	
Integrated ASW Avionic	A-NEW Eng. Development; Contr. Def. Prototype Design, Lab Test				Flight Test; NPE	BIS	Operation	
Other Avionics and Equipment	CF; Contract Definition		Test Article Design	Fab.	NPE Contr. Flt. Test	BIS	Operation	

5. LEAD BUREAU: Naval Air Systems Command

6. TECHNICAL DIRECTOR: Commander J.P. Jones (Code PMA-263)

7. PRINCIPAL CONTRACTORS

4. RDT & E FUNDING (000,000)		FY 70 (and prior)	FY 71	FY 72	FY 73	FY 74	FY 75	FY 76	TO COMPLETE
May 69 PCP	1. ANNUAL	8.00	98.66	200.35	138.40	45.68	1.96	2.65	-0-
FY ___	2. CUMULATIVE	8.00	106.66	307.01	445.41	491.09	493.04	495.69	-0-
		FY ___	FY ___	FY ___	FY ___	FY ___	FY ___	[redacted]	TO COMPLETE
	3. ANNUAL								
FY ___	4. CUMULATIVE								

8. CLASSIFICATION STAMP

*Includes S-4 A-NEW (P.E. 6.32.03.30.2)

FIGURE 3-2 SAMPLE TDP SUMMARY (PAGE 2.1)

T.D.P. SUMMARY (Page 2.2)

CLASSIFICATION STAMP

8. MAJOR MILESTONES	FY 70	FY 71	FY 72	FY 73	FY 74	FY 75	FY 76	FY 77
1. SOR 31-09 issued (December 1968)								
2. RFP for Engine Advanced Development (March 1969)								
3. Initial PCP Submitted (May 1969)								
4. Initial TDP Submitted	o							
5. Avionics System Development Specification Compl.	o							
6. RFP issued for Contract Definition	o							
7. Contract Definition Contracts Signed	o							
8. Proposals Rec'd for Engine Engineering Development		o						
9. CD studies & Engineering Development Proposals Rec'd		o						
10. Prelim. Military Spec. for Avionics Sys. Completed		o						
11. Engine Engineering Development Initiated		o						
12. Weapon System Development Contract Awarded		o						
13. First Full-Scale Engine Run Completed			o					
14. Weapon System Mockup Review Conducted			o					
15. Avionics Development Flight Test Initiated			o					
16. Comprehensive Weapon System Review				o				
17. Award Weapon System Initial Production Contract				o				
18. Engine Preliminary Flight Rating Test Completed				o				
19. First R&D Aircraft Flight				o				
20. Engine Military Qualification Test Completed					o			
21. Board of Inspection and Survey Trials Initiated						o		
22. Operational Evaluation Initiated						o		
23. Commence Fleet Delivery							o	
24.								

● COMPLETED ○ NOT COMPLETED ●- - -○ TIME SLIP

9. FY 70 MILESTONES	JUL.	AUG.	SEPT.	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY	JUN.
1. Initial TDP Submitted		o										
2. Begin Advanced Engine Development			o									
3. Avionics Package Development Spec. Completed			o									
4. OSD Program Approval				o								
5. Request Contract Definition Proposals					o							
6. Mid-Term Engine Report Development Brief										o		
7. Avionics Package Specification Updated										o		
8. Begin Contract Definition, Phase B											o	
9.												
10.												
11.												

CLASSIFICATION STAMP

FIGURE 3-3 SAMPLE TDP SUMMARY (PAGE 2.2)

The essential TDP content prescribed by the Secretary of Defense for his management needs includes, as appropriate:

(1) A narrative statement of the requirements, a brief development plan, and statements delineating performance, reliability, compatibility, and maintainability characteristics.

(2) A time schedule of the development and the milestone schedule that forms the basis for reporting under the programming system.

(3) A financial plan for the life of the development, including planned support for all appropriation sources.

Additional TDP content prescribed by CNO for his management needs includes: summary sheets, management plan, block diagram, subsystem characteristics, associated system characteristics, operability and supportability plan, test and evaluation plan, personnel and training plan, safety plan, and production, delivery and installation plan. NAVAIR Instruction 3910.7 on TDP's is currently being revised to add a requirement for an EMC plan.

To meet EMC requirements, TDP's involving equipments capable of electromagnetic emission or response will also require submission of an Application for Frequency Allocation (DD Form 1494) for each such equipment. This application originates in the office of the cognizant project manager and is forwarded via the normal chain of command to CNO for action. In general, the form requires information on frequency ranges, bandwidth of emission and/or reception, pulse characteristics, and geographical area of use. A more detailed discussion of frequency allocations and spectrum signatures appears in Chapter 4.

In view of the bulk and detail of most TDP's, a summary of information of most significance is submitted to higher level management. Figures 3-2 and 3-3 illustrate a TDP summary for a hypothetical project and include electromagnetic environment considerations.

ACQUISITION MANAGEMENT PLAN

The Acquisition Management Plan is a series of management documents covering the life of a system acquisition project from Concept Formulation until the system is struck from inventory. It is the guiding philosophy that charts the course for all participants (i.e., Navy, DoD, program managers, Navy labs, Navy field activities, contractors, supporting universities, operating forces, etc.) and provides continuity as the system passes from one set of personnel to another through the life cycle of system development, acquisition, and use. The life cycle may extend to more than 20 years and the Acquisition Management Plan guides the tasks in each phase of system life cycle, mainly by the level of detail it contains.

Figure 3-4, EMC Phases of a Weapon System Life Cycle, has been prepared to illustrate the integration of EMC/EMI considerations, requirements, investigations, and resolutions into the life cycle. The important standards and specifications related to EMC/EMI are referenced in the lower section of the chart. The time at which each is brought into the life cycle is indicated by the

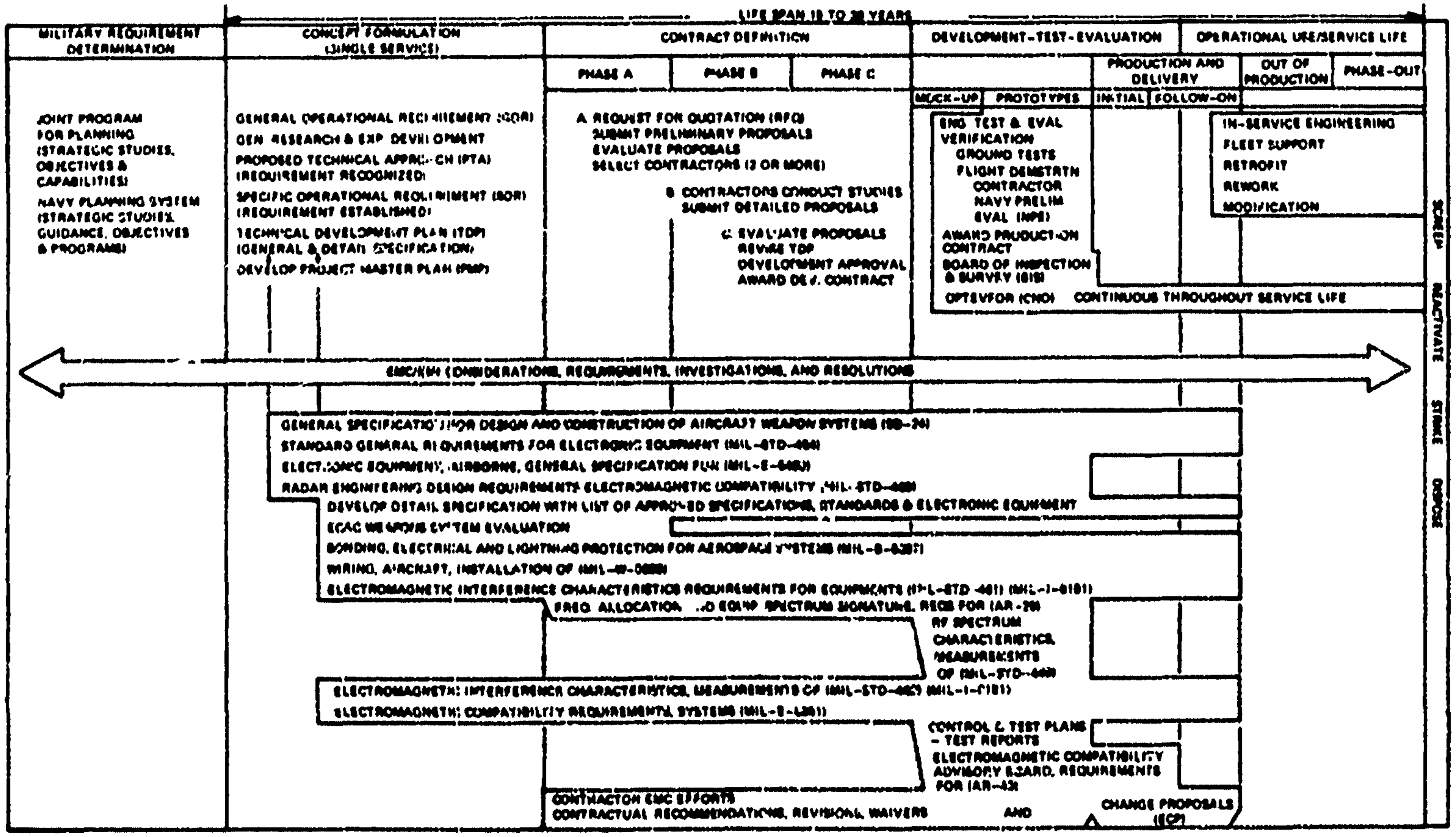


FIGURE 3-4 EMC PHASES OF A WEAPON SYSTEMS LIFE CYCLE

vertical line which enters the upper section of the chart. The duration of the specification or standard in the life cycle is indicated by the length of the horizontal bar referencing the specification, standard, or other element, and its termination is indicated by another vertical line that ties in with the life cycle.

Concept Formulation

Concept Formulation (CF) may begin with a General Operational Requirement (GOR) and proceed through an Exploratory Development Requirement (EDR) to a Specific Operational Requirement (SOR) as shown in Figure 3-4. It might also develop from a GOR into an Exploratory Development Requirement (EDR) and on to a Tentative Specific Operational Requirement (TSOR) before progressing to Proposed Technical Approach (PTA) status. There is also a provision for introduction of the requirement as an unsolicited PTA in response to a GOR in which advanced technology offers a basis for a weapon system. In the CF stage, the future system is identifiable largely by mission envelope and armament requirements, but even at this level initial plans can be made for electromagnetic compatibility. Figure 3-4 shows that at some time during the CF stage, general as well as specific EMC/EMI specifications and standards are applied.

The CF stage of the Acquisition Management Plan defines the project requirements baseline and can be considered an "unsolicited proposal" to DoD in an effort to establish a funded "contract" with DoD to carry out the proposed system acqusition program. Emphasis is on defining operational requirements by stating what a future system must accomplish to solve the project objectives, a feasible conceptual approach that is known to be within the state-of-the-art (in the case of an engineering development), and the overall project that will eventually lead to successful acquisition and introduction of the system. Determination of detailed technical requirements of the specific system is deferred until the Contract Definition (CD) phase. Research, exploratory development, and/or advanced development can all be used to help develop the basis for the concept and development project defined by the CF portion of the Acquisition Management Plan.

Contract Definition (CD) Phase

Contract Definition is a formal procedure preceding full-scale development of large projects. Preliminary engineering and management planning are accomplished during the CD phase to determine realistic design characteristics, cost estimates, schedule estimates, high-risk areas, system interfaces, EMC requirements, and management responsibilities before a contract is awarded. EMC considerations form a significant part of engineering and contract management planning. CD is usually performed by two or more funded and competing contractors collaborating with government representatives. CD may also be performed by in-house laboratories when they will perform the bulk of development effort or, under some circumstances, by a sole-source contractor.

The most important objective of CD is to provide an adequate basis for a decision to ratify or modify the initial approval to proceed with development. The ultimate goal of CD, if development is to be performed by a contractor, is achievable performance and effective specifications, backed by a firm fixed price or fully structured incentive proposal for Engineering or Operational Systems Development.

During CD, design parameters of the projected development begin to take form. Preliminary proposals from prospective development contractors are solicited and evaluated, concepts refined, and requirements for specifications and trade-offs are formulated. During this phase, as part of his response to a Request for Proposal (RFP), each prospective contractor is expected to submit a statement of his EMC engineering capability. This may include details of his EMC organization, EMC investigation and control program, and description of test facilities and capabilities.

When completed, the CD effort will have examined, traded off, and selected the best overall system design from a variety of feasible alternates that will satisfy project requirements defined by Contract Formulation. From the accrued and evaluated data base, the TDP is revised into the form that allows it to become the primary management control and reporting document. At this point, technical details and specification limits for the EMC program are beginning to take definitive form. In sho... CD defines the final design requirements baseline that will be considered in detail in the Systems Development phase that follows. CD attempts to define the design well enough to get a fairly accurate and credible cost and schedule for the entire system life cycle.

In practice, the CF stage of the Acquisition Management Plan is upgraded, detailed for design, costed out, scheduled, and resubmitted to DoD in the form of CD for approval as the follow-on to the original CF approval.

CD neither eliminates nor reduces the requirement for sound system analysis and feasibility studies before entering Engineering or Operational Systems Development. Technical, economic, and military bases for a conditional decision to initiate Engineering or Operational Systems development are established through comprehensive system studies and experimental hardware efforts under Exploratory and Advanced Development, and are prerequisite to a decision to proceed with Engineering or Operational Systems Development. If costs, schedules, design, and CNO prerequisites still appear to be satisfactory, Systems Development can begin.

Systems Development Phase

Engineering Development and Operational Systems Development are concerned with the design, fabrication, test, and evaluation of hardware that finally evolves into the system operational configuration. Engineering Developments include those development programs being engineered for service use but which have not yet been approved for procurement or operation. Operational Systems Development includes research and development effort

directed toward development, engineering, and test of systems, support programs, vehicles, and weapons that have been approved for production and service deployment.

Before a project is approved in either of these categories, engineering data, previously accumulated in Exploratory and Advanced Development, must indicate that it is engineering effort which is required to achieve successful development. If there is uncertainty as to the effectiveness of the proposed systems, or total program lifetime costs, or development time, approval for systems development will normally be withheld. Existence of uncertainty indicates that the project is not ready for Systems Development and that further Exploratory Development or Advanced Development is required.

Projects involving Systems Development will normally invoke a requirement that the selected contractor or Government development agency submit an EMC Control Plan. This plan is expected to state the controlling set of EMC policies that inform each department head, each engineer, each vendor, and the procuring activity of the work effort, areas of emphasis, test and design philosophies, and methods to preclude or solve EMC problems.

When the Systems Development project has reached a level of maturity and cost effectiveness defined as necessary when used by fleet units, and that "first article" configuration has been set as the one for production, the CD portion of the Acquisition Management Plan is upgraded to reflect the following:

(1) The exact system configuration (equipment, trained personnel, facilities, technical data, and interfaces) to be produced in quantity for fleet use.

(2) The production program to produce these quantities.

(3) The fleet training, introduction, and outfitting program.

(4) The logistics program to keep the operational system supplied.

(5) The maintenance program to keep the system operating up to the level of performance effectiveness demonstrated and accepted for production.

(6) The exact means to introduce and approve any necessary change to the system (e.g., changes needed to satisfy EMC requirements).

The upgraded Systems Development portion of the Acquisition Management Plan at this point is in essence the product configuration baseline which the fleet will use until change is found necessary and worth the cost of changing. The Systems Development portion of the Acquisition Management Plan provides the product configuration baseline for that system's in-service engineering effort in that it provides the base or source data for all future EMC and problem analyses, decision making, and correction.

Demonstration and Evaluation Phase

Systems that have undergone Systems Development will be required to demonstrate Systems Performance Effectiveness to the Navy procuring activity before being accepted for operational use. It may be that EMC deficiencies overlooked during development become evident during flight demonstrations, BIS trials, or OPTEVFOR investigations. An aircraft whose components seemed compatible while in the hands of the developer may take on a different

complexion under military conditions, especially in formation or in proximity to other aircraft, ground facilities, or shipboard systems.

A full-scale development contract negotiated as a result of CD is expected to specify the tests by which achievement of Systems Performance Effectiveness is demonstrated. The contractor's profit or fee (including any incentive fees contained in the contract) is contingent upon successful demonstration of performance effectiveness. The devising of practicable and unambiguous demonstrations for such characteristics as reliability, compatibility, maintainability, and supportability is an important task which should be given detailed attention.

Demonstrations normally take the form of Technical Evaluations and Operational Evaluations to demonstrate Systems Performance Effectiveness. These evaluations may be conducted by the Systems Command (SYSCOM), Operational Test and Evaluation Force (OPTEVFOR), the contractor, or, for aircraft, the Board of Inspection and Survey (BIS). "Systems Performance Effectiveness" is defined by the Chief of Naval Material in Reference 1 as, "the probability that the system will perform a stated mission for a specified period of time under explicit environmental conditions." Systems Performance Effectiveness encompasses the reliability, compatibility, maintainability, availability, operability, and supportability of the men and the devices that make up the system.

The environmental conditions under which the system must demonstrate Systems Performance Effectiveness include the EMC/EMI environment as well as the physical (atmospheric) environment. Any system that carries EMC problems into the demonstration and evaluation phase becomes the object of a difficult decision if it is to be placed in production: it must either undergo further engineering or development effort (with possible complications), or deviation must be granted (with consequent degradation of Systems Performance Effectiveness). Those persons faced with this decision will appreciate the value of early entry of effective EMC requirements and control measures into the Acquisition Management Plan.

Systems Production Phase

During the production phase, there is a continuing need to test manufactured or vendor-supplied items to verify continued EMC attributes. A quality assurance test also must be applied to each production specimen to assure continued compliance with EMC requirements.

Each time a significant engineering change is accepted and introduced, the Acquisition Management Plan must be upgraded to reflect:

(1) The new configuration baseline that resulted.

(2) All interacting factors such as those listed in Systems Development subsection.

Any significant modification or relocation of components, equipments, cables, or subsystems will normally subject the system to retest and requalification. The meaning of the term "significant" must be defined for each system.

Operation, Maintenance, and Support Phase

Approval of a system for service use is predicated on its ability to perform its intended function in a fleet environment when operated and maintained by fleet personnel with the training manuals, test equipment, supply, and other support factors considered. Therefore, the operation, maintenance, and support phase calls for meeting two requirements: (1) trained personnel to perform operation, maintenance, and supply, and (2) repair parts, test equipment, and support facilities to keep the system operational. Personnel requirements are funded largely under Program VIII appropriations, and materiel requirements are funded largely under Program VII appropriations.

Personnel training programs, and the manuals and directives concerned with system operation and maintenance, should place sufficient emphasis on EMC matters to ensure that degradation of systems performance effectiveness does not occur due to EMC-related shortcomings in operation and maintenance.

An awareness of EMC considerations should be applied to formulation of operational concepts and doctrine so that operating modes, frequencies, and schedules can be chosen for optimum compatibility. EMC awareness should also include developing capabilities for detecting and solving operational EMC problems, and providing feedback for technical problems to the standards, design, planning, educational, and analytical elements of the EMC program.

Because testing for EMC has not been a common part of fleet maintenance practices heretofore, particular emphasis on the EMC attributes of test equipments, replacement parts, and maintenance facilities may be needed. New test equipments and test facilities designed for EMC are indicated. Repair parts procurement, particularly from "second source" suppliers not originally a party to the research and development phases of the project, must be subjected to appropriate EMC control procedures to ensure that replacement parts having unsatisfactory EMC characteristics are not inserted into the system. The tendency of supply activities to relax specifications for maintenance parts in order to reduce procurement costs is not a good move if it causes reduction of systems performance effectiveness (reliability, compatibility, maintainability, etc.). EMC requirements must provide a continuing input for enforcing and updating the specifications and standards under which replacement parts are procured.

System Termination

When the value of the system to the Navy's and DoD's inventory has depreciated to some specified level, the Acquisition Management Plan is updated for the last time to define how that system is to be phased out of the inventory for the maximum cost-effectiveness. This level must be determined for each system.

Although developed primarily for systems acquisitions, the Acquisition Management Plan sequence is also used for complex and/or costly advanced developments specified by CNM. It is highly recommended that the same approach and format be used for all developments because the process and time

phasing are basic to any development, will ensure against omitting important considerations, and will provide valuable experience for the time when full-scale plans must be used to satisfy CNM and DoD requirements.

PROJECT MASTER PLAN (PMP)

A Project Master Plan (PMP) is a compilation of planning documents prepared by the Project Manager, with assistance from participating organizations and contractors, which places in context the plans, schedules, costs, and scope of all work and resources to be provided by each participating organization. The PMP defines a management approach for acquiring items and services needed to satisfy specified operational requirements. A PMP should be coordinated with corresponding project TDP's because the PMP extends the TDP objectives by emphasizing planning for production, fleet introduction, fleet deployment, and logistics support.

PMP's are required for SECNAV, CNM, and NAVSYSCOM "Designated Projects." A "Designated Project" is one which, because of its importance or critical nature, has been selected for intensified project management. A PMP is a formal life cycle plan which documents the integrated and inter-related tasks (time phased and costed) required of and by all participating organizations, and which is necessary to the success of the weapon system objectives. The PMP assigns tasks to be performed, schedules task completion, assigns activity work, defines task interfaces, sets objectives to be achieved, specifies reports to be submitted, and delineates resources available to the Project Manager. One very important task that should be clearly assigned and delineated by the PMP is that of ensuring that EMC requirements are met not only within the system under consideration but also between the system and other systems with which it must operate.

A PMP (1) encompasses all phases of a weapon system's life from proposal evaluation through development, production, operation, and support, and includes execution plans pertinent to those phases, (2) serves as a single controlling document which forms a complete data package of all essential current and projected events and a time schedule for their accomplishment, and (3) provides a framework for measuring performance against plans, both for the Project Manager in executing his responsibilities and for review and appraisal by higher authority.

NAVMAT Instruction 5200.11A of 10 March 1970 provides guidance for the preparation and implementation of Project Master Plans in the management and execution of appropriate projects within the Naval Material Command. A CNO review is currently being conducted of the feasibility of combining the TDP and PMP into a single document.

DoD FIVE-YEAR DEFENSE PROGRAM

The DoD Five-Year Defense Program (FYDP) is the summation of all approved programs of the Department of Defense components. It includes those areas of the Department of Defense Electromagnetic Compatibility Program for

which each DoD component is responsible as discussed in Chapter 2. The FYDP can be visualized as a three-dimensional matrix in which resource inputs, phased over a five-year period, are combined with military outputs or programs phased over the same period (Figure 3-5). Relating inputs (resources) to outputs (forces) in this way provides the Secretary of Defense (SECDEF) with two major planning dimensions: (1) He can determine the military forces required to counter the existing threat; (2) he can concurrently allocate available resources to those forces.

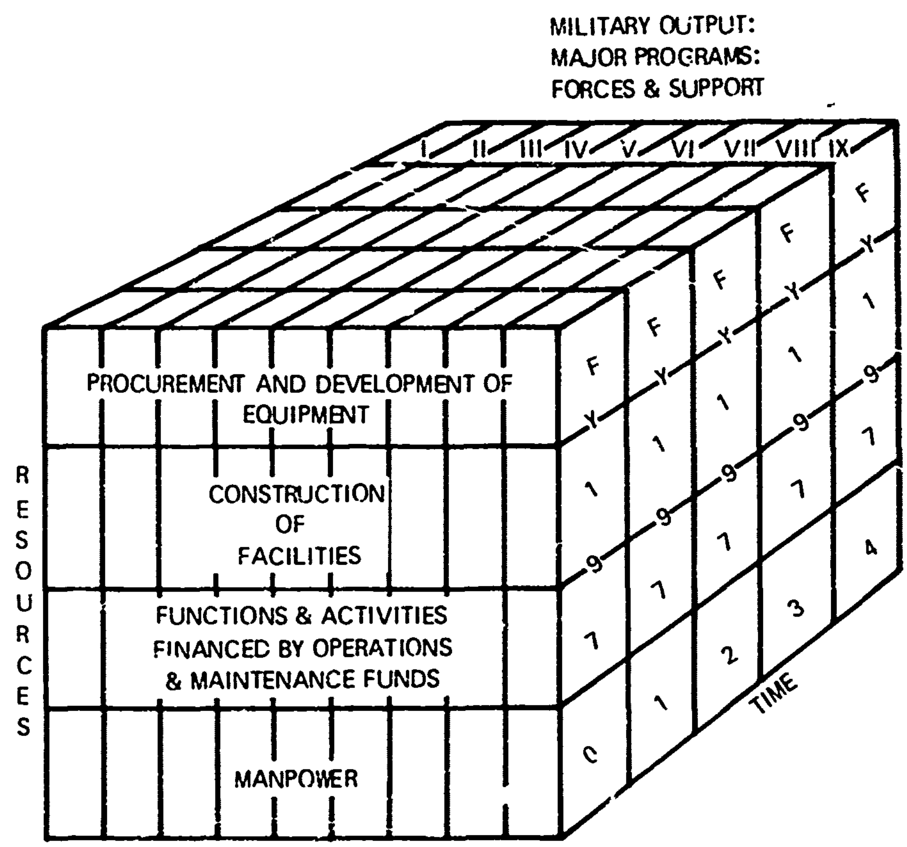


FIGURE 3-5 THE FIVE-YEAR DEFENSE PROGRAM (FYDP)

PROGRAMS AND PROGRAM ELEMENTS

The Program Element is the smallest unit of military output controlled at the DoD level. As defined in DoD Directive 7045.1 (SECNAV 5000.16), a Program Element is "an integrated activity; an identifiable military capability; a force, support activity, research activity, etc., comprising a combination of men, equipment, and facilities." Each RDT&E element is made up of RDT&E projects in the same budget activity. "Fleet Ballistic Missile Systems," and "Recruit Training, Navy" are examples of Program Elements. Program Elements are identified by eight-digit numbers as illustrated in Figure 3-6. Program elements are further resolved into projects which are numbered for naval applications as indicated by NAVAMATINST 3910.12 (series).

Program Elements are grouped to form programs (originally called "program packages"). A DoD program is an interrelated combination of Program Elements designed to accomplish a definite objective or plan which is specific as to the time phasing of what is to be done and the means proposed for its accomplishment. Program Elements of a single program must be considered together because they either complement each other or are close substitutes for one another. The unifying principle of each package of Program Elements is a common mission or set of purposes for the elements involved.

DoD planning has been organized into ten major programs. These ten groups listed below include the total Department of Defense output–the entire force structure needed to meet requirements planned for the next five fiscal years:

(1) Strategic forces
(2) General purpose forces
(3) Intelligence and communications
(4) Airlift/sealift
(5) Guard and reserve forces
(6) Research and development
(7) Central supply and maintenance
(8) Training, medical, and other general personnel activities
(9) Administration and associated activities
(10) Military assistance and support furnished other nations (MAAGs, NATO, etc.)

Within some major programs there are intermediate aggregations of Program Elements which either have closely-related mission characteristics or are often combined for decision-making or display purposes.

Program Element Costs

Because major program decisions are made in terms of Program Elements, the Department of Defense has established a method of relating costs to Program Elements so that the relative economy or efficiency of the elements may be determined. To provide better data for decision making, the total financial requirements for a given Program Element for a fiscal year are lumped together as

PROGRAM CATEGORY ACTIVITY AGGREGATE ELEMENT SERVICE

6 3 2 03 09 2

SERVICE

1 ARMY
2 NAVY
3 MARINE CORPS
4 AIR FORCE

ELEMENT

03 FUEL CELL
06 ARTEMIS
09 HYDROFOILS

AGGREGATE

03 UNDERSEA WARFARE
06 STRIKE WARFARE
09 FLEET SUPPORT
12 COMMAND CONTROL
15 ASTRONAUTICS

ACTIVITY

1 ARMY
2 NAVY
3 MARINE CORPS
4 AIR FORCE

CATEGORY

1 RESEARCH
2 EXPLORATORY DEVELOPMENT
3 ADVANCED DEVELOPMENT
4 ENGINEERING DEVELOPMENT
5 MANAGEMENT AND SUPPORT
6 OPERATIONAL SYSTEMS DEVELOPMENT

PROGRAM

1 STRATEGIC FORCES
2 GENERAL PURPOSE FORCES
3 INTELLIGENCE AND COMMUNICATIONS
4 AIRLIFT AND SEALIFT
5 GUARD AND RESERVE FORCES
6 RESEARCH AND DEVELOPMENT
7 CENTRAL SUPPLY AND MAINTENANCE
8 TRAINING MEDICAL AND OTHER GENERAL PERSONNEL ACTIVITIES
9 ADMINISTRATION AND ASSOCIATED ACTIVITIES
0 MILITARY ASSISTANCE FURNISHED OTHER NATIONS

The Program Element number is an eight digit number, which gives the program number, category number, activity number, aggregate number, and element number as indicated above.

FIGURE 3-6 FORCE STRUCTURE AND PROGRAM ELEMENT NUMBERING

Total Obligational Authority (TOA). TOA includes all funds available for support of a program or Program Element during a year, regardless of appropriation category or the year in which appropriated.

Program costs are broken down into three categories. These are defined in DoD Directive 7045.1 (SECNAV INST 5000.15B), as follows:

Research and Development: Program costs primarily associated with research and development efforts including the development of a new or improved capability to the point where it is ready for operational use. These costs include equipment costs funded under the RDT&E appropriations and related military construction appropriation costs.

Investment: Program costs required beyond the development phase to introduce into operational use a new capability, to procure initial, additional, or replacement equipment for operational forces, or to provide for major modifications of an existing capability. They include procurement appropriation costs except those associated with the operating category defined below, and all military construction appropriation costs except those associated with research and development.

Operating: Program costs necessary to operate and maintain the capability. These costs include military personnel, operation and maintenance, and recurring procurement appropriation costs such as replenishment spares.

RESOURCE CATEGORIES

A resource category is defined as a unique resource or homogeneous group of related procurement, manpower, or construction items. Such categories comprise the second dimension of the planning program shown in Figure 3-5. There are four major types of resource categories: (1) procurement and development of equipment, (2) construction of facilities, (3) functions and activities financed by operation and maintenance appropriations, and (4) manpower. In the same way that the sum of all the Program Elements constitutes the total defense output, so the sum of all the resource categories constitutes the total input. Resource categories inputs and program outputs, taken together, provide a complete picture of the sources and uses of national resources among the various defense activities.

Decisions concerning resource categories are defined in two lists, a Materiel Annex and a Construction Annex. Between them, these lists enable DoD to control the resource costs that influence decisions. The Materiel and Construction Annexes do not apply to Research and Development Program VI allocations. However, RDT&E, Manpower and Operation and Maintenance annexes are developed.

PROGRAM CHANGE PROCESS

Because plans can never be static, provision is made for updating the DoD Five-Year Defense Program as a function of the constantly-evolving program change process. This process establishes procedures for review and approval of proposed changes to the FYDP and for reporting progress toward the anticipated

forces. Through this process, significant changes in Program Elements are brought to the attention of SECDEF for his approval.

Program Change Request (PCR)

The PCR is used to forward requested changes to the FYDP for review and action by the Secretary of Defense. PCR's are required also to reflect program changes which develop from decisions made during review of a Draft Presidential Memorandum (DPM). The PCR, and backup rationale when required, is the means for proposing adjustments to the FYDP. Specifically, changes may be requested to Forces, Total Obligational Authority, or personnel assigned to individual Program Elements in the FYDP. A PCR is also used to "price-out" SECDEF decisions, to support Program Objectives and positions in response to a DPM, and to submit reclamas to SECDEF decisions.

Major Force Issues (MFI)

MFI's are issues concerning proposals which, if approved, would have a major effect, quantitatively and qualitatively, on military forces. MFI's are identified through a JCS/Service SECDEF process. SECDEF then publishes an approved list early in the calendar year for resolution during the calendar cycle. The Initial Draft Presidential Memorandum (IDPM) contains the SECDEF MFI-related tentative decisions and statements of the general basis for these decisions. Recommendations concerning these tentative decisions are submitted to SECDEF by means of line-in, line-out reclama to the IDPM. A final Draft Presidential Memorandum is later promulgated and reflects SECDEF decisions on force levels and procurement.

Program Objective Change Proposal (POCP)

If the PO is to be a viable document for budget development, it should be kept current with changes brought about by new information. Where program dollar amounts in excess of Total Obligational Authority controls are required, identification of equivalent trade-offs within budget activity is generally required. Subject to the foregoing, changes may be made to the PO with SECDEF approval by two methods. By far the most common method is the use of the MEMORANDUM POCP, which is used in conjunction with another basic document such as PCR, reclama to SECDEF decision, memorandum decision, or letter requiring SECDEF signature. The SECDEF decision on the basic document will also determine the status of the MEMORANDUM POCP.

DEVELOPMENT CONCEPT PAPERS (DCP)

SECDEF has approved the use of Development Concept Papers as the instrument for gaining his approval to initiate or continue important DoD development programs. DCP's are ordinarily prepared for all new programs (or major engineering modifications of existing programs) classified as "important." DCP's are also used to obtain SECDEF approval to continue research and

development programs at "critical" decision points in the program. A "critical" decision is either a decision which SECDEF normally makes on an important development program such as a major budget decision, a decision to conduct a Contract Definition, or a decision to deploy, and hence to go from Engineering Development to Operational Systems Development; or one which SECDEF feels he should make as a result of issues or problems that have arisen on the program.

The DCP procedure requires the pre-establishment of decision "thresholds" for each DCP. Thresholds establish the level of change that may occur before a review of the program by SECDEF is warranted. A revised DCP is submitted by DDR&E to SECDEF whenever a threshold is reached, or a significant change occurs in a program before the next critical decision point is reached.

NAVY RDT&E BUDGET PROCESS

Navy programs achieve reality through the budgetary appropriation process by which support funds are provided. It is essential that EMC Program requirements be included in this budgetary appropriation process to assure the availability of adequate funds. The budget process is divided into three phases:

(1) *Formulation:* Planning and developing the budget for the fiscal year beginning one year from the next 1 July. This phase begins when the Comptroller of the Navy issues a call for budget estimates. This call is based on guidance received from the Assistant Secretary of Defense (Comptroller) about 15 June.

(2) *Justification:* Presenting and justifying to Congress the budget for the fiscal year to begin on the approaching 1 July.

(3) *Execution:* Obligating and expending congressionally appropriated funds for the current fiscal year.

RELATION BETWEEN PROGRAMMING AND BUDGETING PROCESSES

Programming has been described as a bridge between planning and budgeting. The DoD Programming System, by relating cost inputs to force outputs and by extending fully costed programs five years into the future, provides information for making decisions that are eventually reflected in budgets. The DoD Programming System is interrelated to the budgetary appropriation system; it does not supplant or supersede it. There is a continuing requirement to be able to convert Navy programs rapidly and accurately from the DoD Programming System structure (Figure 3-6) to the budgetary appropriations format. The Navy Cost Information System (NCIS) has been developed to make this transition. The NCIS is essentially a data bank designed to process and display Navy program and cost information in either of two modes: appropriation structure, or DoD programming structure, using computerized automatic data processing.

Importance of the Budgetary Process

It is within the framework of the budget formulation process that programs must compete for approval and implementation. Approval of a program in the

FYDP is not an automatic guarantee that the program will be funded. Because resources available in any given year are usually less than that required by programs approved in the FYDP, certain programs may be reduced or deleted to reduce the overall budget, or to provide for other programs of higher priority, or because of increased costs of other programs in the budget.

Budgetary Structure

The DoD Programming System was devised to provide information in a form suitable for program decisions and management control. In RDT&E, as distinguished from other appropriations, it is possible early in the programming process to achieve a close relationship between the program structure and the budget structure.

Congress appropriates defense funds for a given fiscal year in an Appropriation Act whose principal subdivisions are:

Title I:	Military Personnel
Title II:	Operation and Maintenance
Title III:	Procurement
Title IV:	Research, Development, Test, and Evaluation
Title V:	Special Foreign Currency Program
Title VI:	General Provisions

The appropriation structure differs somewhat from the DoD Programming System structure and is designed primarily to meet the needs of Congress. Because it is structured on a major end item or hardware basis, it provides Congress a convenient means for correlating RDT&E appropriations with various procurement appropriations.

The actual budget formulation, justification, and execution process is carried on within the framework of the appropriation structure. Program decisions must be converted to appropriation structure for inclusion in budget estimates; decisions made in the course of budget formulation and justification must be reflected in appropriate changes in the FYDP. When the Secretary of Defense presents the DoD budget to Congress, the FYDP which he employs has been adjusted for the past, current, and budget years to agree with the budget document.

Budgetary Formulation

In the budgetary process, the FYDP is revised to reflect the decisions of SECDEF. The revised program is converted to the appropriation structure for the three-year period to be presented in the budget and is supported by detailed shopping lists of items and dollars. In the budgeting phase of the planning-programming-budgeting process, such things as production schedules, prices, lead-time, activity rates, personnel grade structure, and training requirements are required to reflect the program proposed for inclusion in the budget.

Budget formulation is characterized by successive review and decision points, with each succeeding review considering a broader context. In this

process, many proposed items are reduced or eliminated. The objective of the process is to produce a budget that provides the best possible military worth and program balance within the limits of anticipated resources.

Budgetary Justification

Justification follows the formulation process described in the previous paragraph. Each budgetary item submitted by any organization to the next higher echelon must be supported by written justification. This justification both supports the inclusion of any given item in the budget and informs higher level officials of the contents of the estimates that they will in turn submit to higher echelons.

Budgetary justifications demonstrate that the proposed estimate is:

(1) Within the framework of legislation and approved administrative guidelines.

(2) Essential to the effective performance of the mission.

(3) The most economical and effective method of accomplishing its purpose.

(4) Feasible with respect to timing and availability of resources.

(5) Substantiated on its merits independent of needs for prior years.

The "reclama" is an extention of budget justification. The reclama is a formal request for restoration of an item deleted by a higher level organization in its review and consolidation process. In general, successful reclama requires improved justification. The reclama makes it possible to save worthwhile programs which were eliminated only because of a faulty justification.

CONGRESSIONAL BUDGET

There are two phases involved in congressional review of budgetary appropriations involving Navy programs for procurement of aircraft and missiles, for shipbuilding and conversion, and for research, development, test, and evaluation. The programs must first be approved through authorizing legislation which is considered by the Committees on Armed Services of the House and Senate (coordinated by the Office of Legislative Affairs). Then formal appropriation of all funds, including those which must be preceded by an authorization act, is considered by the Defense Subcommittee of the Appropriations Committees of both the House and Senate. Formal hearings are conducted at which SECDEF, SECNAV, CNO, and CMC testify on the overall Navy budget, and representatives of the Navy are then questioned on details of the programs and estimates of requirements to support programs in the budget document.

RDT&E APPROPRIATIONS

Initial hearings on RDT&E authorizations are held by the subcommittee on research and development of the House Armed Services Committee. Recommendations of this subcommittee, if accepted by the full Armed Services

Committee, are acted upon by the full House. The Senate Armed Services Committee then conducts its hearings and reports recommendations on the authorization bill as passed by the House. Differences between committee reports of each House are resolved in joint committee meetings. The authorization as enacted establishes the maximum amount which may be appropriated by Congress.

The procedure on appropriations is somewhat similar. The House Appropriations Committee acts first, holds hearings, and recommends an appropriation bill to the House The Senate Appropriations Committee holds hearings and recommends appropriate changes to the appropriation bill as passed by the House. Following these hearings, reclamas can be made for restoration of selected eliminations or reductions made by the House. If there are differences between the Senate bill and the House bill, a meeting is held between designated representatives of each committee and a mutually agreeable position is reached. Upon approval by both houses and signatures by the President, the appropriation bill becomes law.

PREPARATION FOR HEARINGS

Through preliminary liaison with the committee staff, conducted through NAVCOMPT for appropriations committees, and through the Office of Legislative Affairs for all other committees, particular areas of interest and the probable duration of hearings are determined. Principal witnesses submit prepared statements in advance of testimony. These statements are carefully reviewed internally within the Navy and Office of SECDEF before submission to the committee.

The Assistant Secretary of the Navy (Research and Development) is the principal witness in support of the Navy RDT&E program and appropriation requests before both the authorization and appropriation committees. He is supported by his top advisors from the RDT&E field. Hearings on the RDT&E appropriation are almost invariably conducted in executive session owing to the security classification of the matters discussed.

PROCUREMENT OF RDT&E EFFORT

FYDP Program VI, Research and Development, is divided into six funding categories of R&D effort (Figure 3-6). A Program Element may be funded in more than one category. For example, the NAVAIR EMC Analysis and Predictions Program appears under categories 6.2 and 6.5. The six R&D funding categories are defined as follows:

6.1 RESEARCH - Includes all effort directed toward increased knowledge of natural phenomena and environment, and effort directed toward the solution of problems in the physical, behavorial, and social sciences that have no clear direct military application. It includes all basic research and applied research that is directed toward the expansion of knowledge in various scientific areas. It does not include efforts to prove the feasibility of solutions or problems of immediate military importance or time-oriented investigations and developments.

6.2 EXPLORATORY DEVELOPMENT - Includes all effort to solve specific military problems, short of major development projects. Exploratory development may vary from fairly fundamental applied research to quite sophisticated breadboard hardware, study, programming, and planning efforts. It includes studies, investigations, and minor development effort. The dominant requirement of this category of effort is that it be pointed toward specific military problems, with a view toward developing and evaluating the feasibility and practicability of proposed solutions and determining their parameters.

6.3 ADVANCED DEVELOPMENT - Includes all projects that have moved into the development of hardware for experimental or operational test. It is characterized by line item projects, and program control is exercised on a project basis. Another characteristic is that the design of such items is directed toward hardware for test or experimentation as opposed to items designated and engineered for eventual Service use.

6.4 ENGINEERING DEVELOPMENT - Includes those development programs being engineered for Service use but which have not yet been approved for procurement or operation. This category is characterized by major line item projects, and program control is exercised by review of individual projects.

6.5 MANAGEMENT AND SUPPORT - Includes research and development effort directed toward support of installations or operations required for general research and development. Included would be test ranges, military construction, maintenance support of laboratories, operations, and maintenance of test aircraft and ships. Costs of laboratory personnel, either in-house or contract-operated, would be assigned to appropriate projects or as a line item in research, exploratory development, or advanced development programs, as appropriate. Military construction costs directly related to a major development program will be included in the appropriate element.

6.6 OPERATIONAL SYSTEM DEVELOPMENT - Includes research and development directed toward development, engineering and test of systems, support programs, vehicles, and weapons that have been approved for production and service use. This area is included for convenience in considering all RDT&E projects. All items in this area are major line item projects that appear as RDT&E Costs of Weapon Systems Elements in other programs.

NAVAL FIELD ACTIVITIES

A major portion of Navy RDT&E effort, including tasks in the EMC area, is carried out by in-house RDT&E laboratories. Though technically a systems command or office does not "contract" with its laboratories, it does reach agreement with them on such things as tasks, cost, and time. In exercising management guidance, a Systems Command transmits work requirements to its laboratories by task assignments, after agreement has been reached through informal negotiations. Task documents set forth the level of effort and the schedule, together with all necessary technical details to enable the laboratory to accomplish the work.

The extensive in-house RDT&E field organization of the Navy, unique in

size and scope among the military departments, provides an important portion of its RDT&E competence. The present complex of Navy RDT&E field activities employs more than 9,000 scientists and engineers. This complex represents about 30 percent of the annual Navy budget for RDT&E projects. Navy RDT&E field activities perform a wide variety of essential tasks and missions ranging from basic research to support of specialized equipment in the fleet.

The basic purpose of in-house RDT&E field activities is to provide the fleet with the most effective weapons and equipment possible. To fulfill their obligation to the fleet and to further advance the technical data base, Navy field activities must not only be producers of science and technology, but they must also be cognizant of present and future operational requirements of the fleet. The basic task of Navy field activities is to provide the most effective weapons and delivery vehicles that men can operate under the stress of combat. An extensive discussion of Navy field activity organization and mission appears in the RDT&E Management Guide (NAVSO P-2457) Appendix F.

MILITARY INTERDEPARTMENTAL PROCUREMENT REQUESTS (MIPR)

The Military Interdepartmental Procurement Request (MIPR) provides one of several means by which the Navy can procure RDT&E effort other than through its own contractors and in-house laboratories. When a requiring department, such as the Navy, desires to participate in the RDT&E effort of a procuring department other than the Navy without preparing a separate contract, the MIPR (DD Form 448) provides a means to do so. For example, the NAVAIR EMC staff is currently participating in, and supporting with funds, an Air Force project for investigating natural RF interference and electrical hazards for military aerospace vehicles.

The primary objective of a MIPR is to obtain maximum military economy through the consolidation of requirements and elimination of competitive purchases. The procuring department consolidates in one contract its own requirements plus requirements received via MIPR. Funds are then transferred by the requiring department to the procuring department. The procuring department is authorized to create obligations against the funds cited without further referral to the requiring department.

When the Navy is the requiring department, it is essential that communication be set up between the requiring department (Navy) and the procuring department (Army, for example) to deal with EMC requirements and problems.

Similar coordinated procurement procedures exist for arrangements with NASA, FAA, AEC, and other Federal agencies outside the Department of Defense.

Under the Military Assistance Program, foreign research programs showing promise may be the subject of cost sharing or aid contributions which entitle us to share the results, reports, and other data. NATO-coordinated arrangements may entitle us to data and production items. If the request has an International Balance of Payments impact, an estimate of the amount of the impact must be stated.

INDUSTRIAL RDT&E EFFORT

By nature and definition, research and exploratory development involves effort to extend the field of scientific knowledge and its applications. Because the result cannot be foreseen, achievement of a specified goal usually cannot be made a condition of the contract. A research "contract" usually covers a specified investigative effort, rather than achievement of any foreseen result.

Partially due to problems involved in contracting for a specified substantive result, most research and exploratory development effort is performed in-house, particularly in laboratories. A portion of this work is, however, performed by non-government institutions. Contracting for research and exploratory development is treated separately from contracting for systems development because the problems are different and approaches for one are not necessarily applicable to the other. However, a clear definition of the Government's goals or requirements is essential to any procurement contract.

In Navy offices and Systems Commands, various industry-generated ideas and proposals are received, either in response to a Request for Proposal (RFP) or as an unsolicited proposal. They stimulate creative ideas that ultimately assist in fulfilling the needs of the Navy. Such proposals are carefully screened and evaluated in the light of applicability and availability of funds. Ideas submitted in unsolicited proposals may result in industry participating in R&D contracts or formal mutual exchange programs. The Naval Air Systems Command issues the R&D Planning Guide which covers weapon systems and the R&D Long-Range Technical Area Plan. If a contractor desires, he may undertake an unfunded study project based on these plans and provide a report. As a result of the report, program action may be started.

When the Government contracts for research by industry, it is buying knowledge to increase the basic reservoir available for meeting defense needs. Therefore, full disclosure of all information obtained under research programs should be a requirement in such contracts. The information becomes Government property, to be made available under controlled conditions to those who need it.

TESTING AND EVALUATING WEAPONS AND WEAPONS SYSTEMS

The processes of test and evaluation are used for a variety of purposes in the Navy. From the RDT&E standpoint, perhaps the most important is securing approval for service use of the product of development. A second consideration is support of research and development projects by operational testing organizations and units of the operating forces.

Testing begins early in the life of a system, with the producer's checks of the "breadboard" models. These early tests verify EMC mathematical predictions and provide guidance for design refinements necessary to achieve compatibility. EMC tests continue through the development stages, following EMC Control Plans and EMC Test Plans such as those in Appendices A through D. Weaknesses and deficiencies enter a feedback loop leading to revised design and retesting.

The producer's final full-scale testing to demonstrate compliance with contractual EMC requirements, in the form of a Navy Preliminary Evaluation, is conducted using the producer's facilities and coordinated with Navy representatives. The producer's test results, validated by the Navy representatives, are used as the basis for the EMC portions (and other parts) of the BIS trials.

Fleet services needed to support RDT&E projects are provided by units permanently assigned to COMOPTEVFOR, such as air development squadrons, or by other forces assigned for special purposes in the Fleet Commander's Quarterly Employment Schedules. Additional services may at times be supplied by other military departments for specialized tests.

TYPES OF TESTS

OPNAV Instruction 3960.1C "Prosecution by the Operating Forces of CNO-Assigned RDT&E Projects," establishes responsibilities and procedures for conduct of tests and investigations by operating forces. This directive defines in detail different types of investigations, evaluation projects, and tests. These can be grouped into the following classes:

(1) Development Assist Tests are projects which, in effect, provide fleet services when a developing agency needs to conduct tests in an operational environment before continuing with the development effort.

(2) Operational Evaluations are the service acceptance tests which culminate the RDT&E effort for each development.

(3) Research/Operational Investigations are used to provide fleet services when needed for broad research purposes which are not directly connected with a current equipment development.

Other tests, such as production tests designed to see if material meets specifications and qualification tests on samples by prospective bidders seeking certification, are conducted before material is ready for fleet tests. One of the principles of RDT&E management which has been reaffirmed over the years is "Test early and test often." Testing can be considered as starting with feasibility studies and theoretical tests of concepts long before actual hardware is developed. Testing continues even after the material is accepted for service use.

ORGANIZATIONS PERFORMING TEST AND EVALUATION

Appendix E of Department of the Navy RDT&E Management Guide (NAVSO P-2457) provides an extensive list of government organizations performing test and evaluation. This appendix discusses the mission and function of these organizations, not all of which are concerned with electronic systems or EMC. Many of the agencies, systems commands, and offices listed maintain laboratories, test centers, or test ranges. In addition to those listed, test and evaluation is performed on an "as needed" basis by maintenance activities such as shipyards, overhaul and repair facilities, ordnance plants, and type commands. Test and evaluation may also be carried out by commercial laboratories,

contractor establishments, or by special committees set up under such organizations as EIA or SAE.

APPROVAL FOR SERVICE USE

Approval for service use is based on service acceptance tests to demonstrate the ability of a system to perform its function in a fleet environment when operated and maintained by fleet personnel with the training manuals, test equipment, supply, and other support factors considered. These tests provide information on military performance effectiveness in relation to cost effectiveness, personnel requirements, training requirements, operability, compatibility, and maintainability in a fleet environment.

Requirements and procedures for approval for service use are set forth in OPNAV Instruction 4720.9, "Approval of Material for Service Use." This instruction states that to be approved for service use, a weapon system or other material must successfully undergo operational and/or technical evaluation wherein it must:

(1) Demonstrate its ability to perform reliably in accordance with its designed specifications and in its intended operational environment.

(2) Demonstrate its ability to be effectively operated and maintained by the level of personnel skill anticipated to be available under service conditions.

(3) Provide sufficient evidence that it can be supported logically in a deployed status.

A detailed requirement under (1) above for electrical and electronic material is that it meet EMC/EMI standards set forth in applicable military specifications. Suitability for service acceptance is determined by a review of the results of operational evaluation and, where applicable, by experience gained from use of pilot production equipment. Responsibility for the decision as to suitability for service use is assigned to DCNO (Air) for aircraft and supporting equipment, and to DCNO (Fleet Operations and Readiness) for all other equipment. In certain instances procurement may be authorized prior to formal approval for service use. However, it is the CNO general policy that weapon systems and equipment not be approved for service use until they have proved their effectiveness by operational test and evaluation.

BOARD OF INSPECTION AND SURVEY

Board of Inspection and Survey (BIS) trials are operational readiness tests conducted on complete ships and aircraft. The BIS trial is a step by which a ship or aircraft passes from R&D to operational status.

A BIS trial for an aircraft differs greatly in scope and procedure from that for a ship. It would be extremely hazardous to take an aircraft aboard a carrier before its flight characteristics are well known and the pilots thoroughly indoctrinated. Therefore, BIS trials for aircraft are more extensive.

Before aircraft BIS trials, the contractor's own pilots demonstrate at the company's facility or at a test center, safety of flight, electromagnetic compatibility, and ability of the plane to perform its mission. During this time,

the Navy Preliminary Evaluation begins, in which Navy test pilots fly the aircraft to determine its readiness for BIS trials. When NAVAIRSYSCOM is satisfied with the performance of the aircraft, BIS trials begin. These are usually carried on for about 60 days to determine whether the aircraft and its support equipment can perform its basic mission and is suitable for service use. BIS trials include tests to verify that the aircraft electronic systems and its support equipment meet contractual EMC requirements. Some aspects of BIS trials may continue after the INSURV Board has endorsed the aircraft as ready for fleet introduction.

OPERATIONAL PROBLEMS

One of the most urgent problems of naval operating forces is the management of the electromagnetic environment in which tactical forces operate. Tactical employment of electromagnetic equipment is essential to every aspect of naval warfare, and interference can degrade tactical effectiveness. Planning and development of ship and aircraft electronic systems has in many cases been a reaction to meet specific independent needs, often without adequate regard for compatibility with the total electromagnetic environment. The urgency of immediate problems has frequently led to actions which overlook the more involved considerations of systems integration. This has encouraged uncoordinated proliferation of electronic problems and has created a multitude of budget items in all appropriations categories. As a result, electromagnetic design, concepts, and doctrine for both offense and defense has not been optimum.

Even after an electronic system has been put in operation, further EMC problems may become apparent. These problems may result from:

(1) Failure to anticipate realistically all EMC requirements in standards, specifications, and tests.

(2) EMC deficiencies that arise after operation or maintenance.

(3) Changes in the system's operating environment.

(4) New missions being added to the mission envelope.

(5) New or different equipments installed in the ship or aircraft.

(6) Maintenance procedures that do not regard systems compatibility requirements.

TACTICAL ELECTROMAGNETIC PROGRAM OFFICE

To provide direction and planning for the fleet's electromagnetic needs, the Chief of Naval Operations has established within the Navy Department a single office to coordinate all requirements for the development, procurement, installation, training, and use of all electromagnetic systems in the various forces, ships, and aircraft. The Director, Tactical Electromagnetic Programs (OP-093) is responsible for:

(1) Formulating a total electromagnetic plan for the Navy, setting forth requirements and priorities.

(2) Coordinating requirements related to electromagnetic systems for ships and aircraft.

(3) Providing a single point within the office of CNO to ensure the development of coordinated and effective electromagnetic systems for conducting naval warfare.

(4) Providing close collaboration with the Director, Electronic Warfare and Tactical Command Systems (OP-35), with the Anti-ship Missile Defense Coordinator (OP-03G), and with each DCNO, ACNO, and DMSO to ensure that programs under their cognizance are compatible with electromagnetic requirements.

The Director, Tactical Electromagnetic Programs (OP-093) performs the following functions:

(1) Develops, promulgates, and regularly updates a total Navy-wide electromagnetic plan. Coordinates and provides guidance to the total Navy electromagnetic plan and ensures that all planning and programming conforms with this plan.

(2) Maintains close liaison with the Naval Intelligence Command and develops intelligence requirements to assure that vital intelligence estimates and data on the electromagnetic threat environment are obtained.

(3) Establishes electromagnetic systems integration, emission control policies, and emission parameters. Defines varying conditions of emission control and operational performance standards for implementing these conditions.

(4) Continually appraises the ability of the air and surface operating forces to control emissions and recommends necessary corrective action.

(5) Evaluates fleet electromagnetic interference problems and recommends necessary corrective action.

(6) Advises, coordinates with, and provides guidance to the DCNO (Air) and the Director, Command Support Programs in the establishment of airborne and shipboard electromagnetic requirements as they relate to electromagnetic integration and emission control requirements of the fleet.

(7) Recommends for promulgation in the Naval Warfare Publication series, tactics, doctrine, and procedures concerning naval electromagnetic systems.

(8) Serves as a principal advisor on electromagnetic matters to the Ship Characteristics Board. Reviews the electromagnetic portion of the Five-Year Shipbuilding and Conversion Program and the Fleet Modernization Program. When designated as the representative of the DCNO (Fleet Operations and Readiness), serves as a member of the Ship Characteristics Board and assumes associate membership at other times as tactical electromagnetic coordinator.

The Director, Tactical Electromagnetic Programs also acts as Chairman of the Tactical Electromagnetic Readiness Advisory Council (TERAC). The Council is comprised of representatives from the offices of the Chief of Naval Material and each of the systems commands and the Anti-Ship Missile Defense Coordinator. The purpose of TERAC is to aid in the development of the Navy electromagnetic plan as well as to develop or assess proposals involving electromagnetic systems before presentation to the ship or aircraft

characteristics board. The views and recommendations of TERAC will be available to the characteristics boards as an aid in decisionmaking.

FLEET OPERATION AND MAINTENANCE

If EMC deficiencies become evident during operation and maintenance of operational aircraft, it may be necessary to modify or rework the aircraft to satisfy compatibility requirements. Two courses of action are available, based upon services which can be provided. (1) Representatives from the producing activity, working in conjunction with operating or maintenance organizations, may conduct additional tests and evaluations to determine remedial measures, or (2) the aircraft may be returned to the Naval Air Test Center at Patuxent River, Maryland, for additional tests and evaluation. Corrective action may call for modifications that can be accomplished locally, or it may require that aircraft already produced be returned to a rework facility or to the producer for a retrofit. Aircraft being produced, or to be produced, should, within the contract framework, incorporate the remedial measures at the producer's faciltiy, and the EMC test plan revised accordingly

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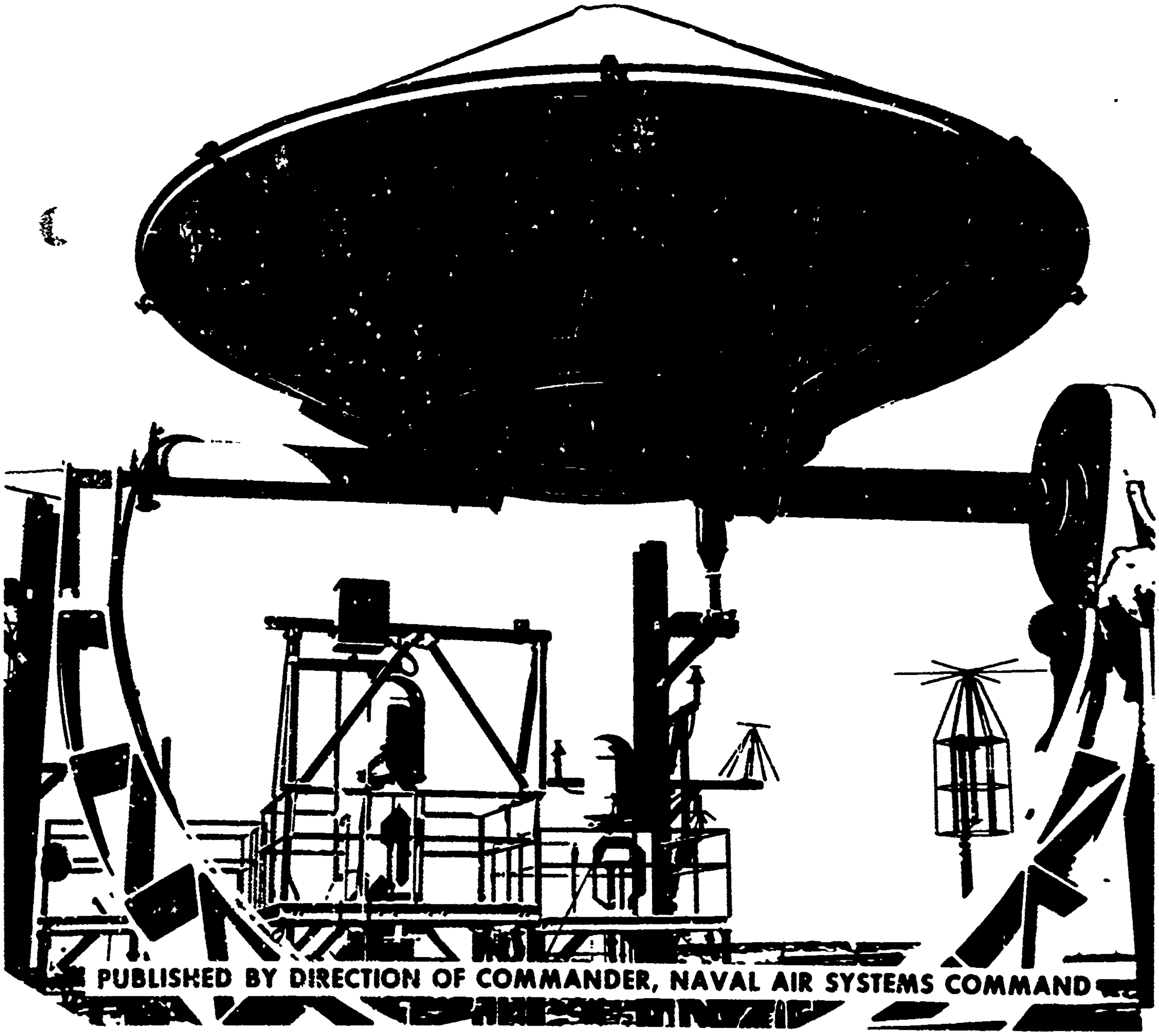
NAVAIR 5335

NAVAL AIR SYSTEMS COMMAND

ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 4



PUBLISHED BY DIRECTION OF COMMANDER, NAVAL AIR SYSTEMS COMMAND

CHAPTER 4
EMC PROGRAM CONSIDERATIONS

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ILLUSTRATIONS

EMC PROGRAM IMPLEMENTATION AND COST

Adequate evaluation of any program requires a basic understanding of its underlying principles in order to place the parts of the program in proper perspective. All new and current Navy programs for research, development, production, or modification of equipments or systems involving electronics will impose requirements for electromagnetic compatibility. Applicable compatibility requirements run the gamut from frequency channel assignments to detailed technical procedures for controlling emission of, or susceptibility to, any or all electromagnetic energy. The principles in an electromagnetic compatibility program are interdisciplinary and involve the costs and economics of implementation. Thus, failure to consider all applicable factors can result in expensive program slippages and cost overruns.

To be effective and economical, the EMC program must be well integrated into the project it is intended to serve. Its goals must be well defined, and its objectives must be clearly understood by management as well as all concerned engineering groups. These requirements may be met most effectively by providing for an EMC organization within the management and engineering structure.

A development or production project requiring an EMC program should be organized with the authority and responsibility to integrate EMC design practices into the project. This degree of authority must usually be derived from the authority of the Director of Engineering (or equivalent) through the Project Director. The goal of this EMC organization is the achievement of these six principal objectives:

1. Establish sources of EMC information that will provide engineering, manufacturing, and testing organizations with a complete definition of the EMC environment in which the system, subsystem, or component must operate.

2. Provide interpretation and application of specifications, engineering methods, and testing procedures that will make it possible and feasible to plan the initial design of each equipment or system so that it will operate compatibly with all other electronic and electrical devices in its intended operational environment.

3. Develop and apply methods to predict quantitatively the amount of operational degradation resulting from mutual interference that may be encountered in envisioned operational situations and to develop means through

improved operational doctrine, frequency management, and design techniques that will permit effective operation of all essential electronic and electrical systems.

4. Develop an EMC Control Plan that will assure eventual achievement of a compatible system by placing into effect the methods and procedures required in various phases of the program to meet contractual requirements, and that will communicate to all responsible contractor and subcontractor personnel the emphasis and design guides to use to avoid interference problems.

5. Establish and implement an educational program that will indoctrinate personnel at all levels of operation and management concerning all aspects of electromagnetic compatibility program, its nature, its importance in the program, and the management, engineering, and operational factors involved in its solution.

6. Coordination with co-contractors, sub-contractors, and suppliers through review boards.

In short, the objectives encompass project requirements for gathering EMC information, dissemination and application of the information, prediction of interference problems and suggested methods for their remedies, development of an overall EMC control document, and training and indoctrination of personnel in EMC techniques.

In negotiating for a procurement or development project, a bidder's EMC group should be represented on the proposal response team to make sure that the EMC portion of the project receives adequate technical and cost consideration. All too often the bid team does not have an EMC representative, and the EMC portion is underbid or not allowed for at all. Then when detailed EMC requirements are invoked by the contract, EMC activities may receive insufficient support or no support at all and result in a totally inadequate EMC effort.

Once all the factors having a bearing on electromagnetic compatibility have been given careful consideration, an EMC program directed at achieving the established objectives can be developed. The EMC program is a subject of contract negotiations between the procuring activity and the producing activity. Negotiations on contracts that include an EMC program are based on cost considerations compared to systems effectiveness. The proposed EMC program is then reviewed by all responsible management agencies to determine the economic feasibility and operational practicality.

Because of high component density, EMC problems are especially severe in avionics systems. A compatible airborne system can be achieved by adequate care in the initial planning, design, and development, coupled with enforcement of an integrated EMC control plan and a well-oriented educational program that will ensure complete indoctrination of all responsible personnel with the policies, methods, philosophies, procedures, responsibilities, and channels of communication. The added costs of an EMC program applied during the R&D and production phases can be considered acceptable from the cost effectiveness point of view if the improved electromagnetic compatibility increases system effectiveness and performance reliability.

EMC INFORMATION SOURCES

The first objective, the gathering of information, is divided into what and where. What EMC information does the project require? Basically, it needs the information necessary to satisfy the other objectives. This includes data on the environment in which the system under design will operate, engineering data, specifications, test philosophies, customer requirements, and educational material. The second problem, where to get the necessary information, often turns out to be the major headache. Information about the environment should come from the customer, including information about systems built by other contractors. Various Government agencies in addition to the armed services, maintain large EMC data banks where information about specific equipments can be obtained. One of these, the Electromagnetic Compatibility Analysis Center (ECAC), collects spectrum signature information on many types of transmitters and receivers, both commercial and military.

COMPLIANCE WITH EMC SPECIFICATIONS

The second objective of the EMC program is the interpretation, dissemination, and application of information on specifications, design techniques, test methods, and tolerances. Necessary data must be furnished to design and development engineering personnel to ensure that the EMC requirements are included in the initial design. Specifications relating to EMC must be interpreted and applied specifically to the project at hand. Sample forms for this effort appear in the EMC Control Plan and EMC Test Plan sections of this manual. Once the signal characteristics of the particular environment have been identified and the signal parameters for the system under design have been specified, a simulation program can be devised and used to test the electromagnetic compatibility of the system.

A series of DoD, governmental, and industrial standards has been prepared, and various combinations invoked contractually covering compatibility of equipments and subsystems within a system, and between the system and its environment. Contracts for the development, production, or modification of equipments and systems that radiate or receive electromagnetic energy should include definitive specifications and requirements for EMC, not only within the specific equipment or system, but with respect to its specified operational environment.

Because of the seriousness of current EMC problems and the expected increase in number and complexity of electronic or electrical systems, specifications and requirements are likely to become more stringent. Current levels of electromagnetic interference can no longer be tolerated if realistic reliability goals and safety standards are to be met. The intent of interference control specifications is to ensure the compatibility of multiple electronic equipments and systems in the environment in which they are collocated.

Before requirements can be specified regarding the electromagnetic compatibility of a new system with its intended environment, the contractor should be provided with:

1. A quantitative statement of signals that are likely to be encountered in the environment, described in terms of frequency, bandwidth, energy level, and time relationship

2. A description of vulnerable parts of other systems within the environment and their susceptibility to interfering signals

3. A definite specification of tests that can be made in the contractor's plant to prove compliance with the requirement.

EMC ANALYSIS AND PREDICTION

The third objective of the EMC program is analysis and prediction of compatibility problems. To arrive at a valid appraisal, the cost of an EMC program must be weighed against its value. It is far less costly to analyze, predict, and control problems related to EMC at the outset than to be overtaken by problems late in the schedule – problems whose solution will probably be extensive and time-consuming.

EMC cost considerations are based on satisfying the program objectives in all six phases of program activity:

1. Concept formulation
2. Contract definition
3. System design and development
4. System evaluation and test
5. System production and quality assurance
6. System operation and maintenance

These activities fall into two major areas: analysis and control. Understandably, during certain phases of a project, EMC activity will center around one area exclusively, while in other phases, simultaneous activity of both types will be necessary. Accurate and objective prediction must ensure that most design deficiencies, weaknesses, or pitfalls will be uncovered and if possible corrected before they reach the hardware stage.

EMC analysis and prediction is derived from the mission profile, which is a detailed, logically interrelated, step-by-step description of the sequence of critical events of a mission. From a mission profile, it is possible to estimate the operational characteristics required of the system and to determine the types and capabilities of subsystems and equipments needed. This in turn leads to a prediction of the emission and susceptibility characteristics of the equipments involved and of the operational degradation that can occur during worst-condition mission events.

EMC analysis can begin once a mission envelope and the design parameters of participating systems have been specified. Because the inherent electromagnetic compatibility of a system is one of the parameters of the design, a system matrix or mathematical model can be constructed for analysis. This fact illustrates that one aspect of EMC engineering is service-oriented. It can help the designer or the manager to measure important characteristics of a given design and occasionally provide insight into how particular designs or procedures might be altered to improve the electromagnetic compatibility of the systems.

The procedures suggested herein are intended to illustrate those elements that are required to arrive at an accurate prediction. The principal elements of these approaches are the matters of defining spectrum signatures, of developing a mathematical electromagnetic compatibility model for the overall operation, and systematically linking these elements to the world of real equipment and available test data.

EMC Analysis and Control During Concept Formulation

In the early creative stages of a project, General Operational Requirements (GORs), Specific Operational Requirements (SORs), or Technical Development Plans (TDPs) undergo a study from which a weapon system concept is formulated. A mission profile for the projected weapon system is generated and a predicted system capability is planned. The program at this point may call for research and development to determine the technical feasibility of the projected capability, or it may include plans for production of an operational system. Planning and procurement activities are usually supported and augmented by invited prospective contractors. In fact, it may be the prospective contractor who introduces the system concept.

As part of concept formulation, the first predictions or estimates are made regarding EMC technical feasibility and comparative costs of various approaches. Concept formulation includes planning for communications, navigation, and identification subsystems; radar, EMC, and penetration aids subsystems; weapon and navigation computer subsystems; and any other avionics subsystems needed to satisfy the mission envelope.

Analytical prediction studies are based on available technical data related to the proposed design configuration and intended operational environment. The Electromagnetic Compatibility Analysis Center (ECAC) maintains an EMC data base and analysis capability to serve the Department of Defense for integration of systems with a geographical environment model. Data base includes spectrum and susceptibility characterisitcs of most current military equipments and of environmental conditions of many geographical areas in which the proposed system may operate. Individual branches and commands of the Armed Forces may have enough data base and analysis capability to meet the needs of the proposed system.

For systems involving advanced technology for which adequate data base is not available, it becomes necessary to make expert assumptions regarding the operational environment, probable susceptibility problems, and attainable levels of interference control. The urgency normally associated with proposal predictions almost dictates the use of electronic analytical facilities. Mathematical models can be evolved by computer analysis, with a confidence level commensurate with the available data base and thoroughness of analysis. If analysis capability is not available in-house, it may be possible to contract for this service with any of several commercial activities having technical competence in EMC consultation and analysis.

EMC Analysis and Control as Part of Contract Definition

Most of the effort associated with the preliminary analysis involves the expense of adequate definition of the disturbance or electromagnetic environment and the establishment of criteria for success and failure. When a contract is awarded, there must be mutual agreement between customer and contractor on these fundamental considerations. It is important that the contractor understand what is and what is not technically essential, desirable, feasible, or even possible.

In the proposal phase, only large EMC problems should be considered. If necessary, the original design philosophy must be reoriented at the outset to eliminate any obvious interference. A review of the adequacy of the available evaluation facilities is in order at this time. The bidder's demonstrated sophistication and sensitivity regarding EMC problems, as evidenced by proper emphasis in the proposal document, could be the deciding factor in the award of a contract.

Up to this point, emphasis has been directed toward establishment of an EMC program that starts with the system concept and is carried through the subsystem and component development to final integration as a system. The intent of interference control specifications is to make possible the compatible collocation of multiple electronic equipments. However, the combination of components and subsystems is unique for each development program, and compatibility problems peculiar to that combination must be considered. Therefore, a realistic interpretation of EMC specifications should be made a part of contract definition, in order to tailor the specifications to the peculiar requirements of each development program.

EMC Analysis and Control During Design and Development

After award of a contract, a detailed functional design study is made of the overall system and its constituent subassemblies. EMC parameters are defined, major contributory factors are analyzed, and the necessary goals are established. A preliminary budgeting of the total EMC allowance is made. Detailed EMC specifications for the planned system are then formulated and EMC requirements and testing procedures for purchased items are prepared. Specific requirements of equipment and facilities are also detailed. Liaison contacts with the cogent hardware organizations are established and EMC philosophy and goals are conveyed to them.

The product of activity in the design study phase is the EMC Control Plan which, according to MIL-E-6051D or MIL-STD-461A, must be submitted to the customer by the contractor within a specified time after a contract award. This plan describes the interference control program and the engineering design procedures and techniques that will be used in complying with MIL-E-6051 or with other applicable military specifications. Typical of the types of information to be included in the EMC Control Plan are contractor methods for system grounding, bonding, shielding, and filtering; methods of eliminating spurious emanations, responses, and resonances; suppression data on high-power RF

equipment or sealed equipment; and descriptions of critical components.

During the hardware design phase, close attention to EMC precautions must be paid by the various responsible hardware organizations. Value analyses and value engineering principles should be applied to assure that the product delivered will meet EMC requirements. One goal in this phase is to promulgate EMC design guidelines or EMC design standards to simplify the designer's task or make routine some of the labor involved. Achievement of this goal depends upon acquisition of reliable EMC data.

Design review and design analysis of parts, circuitry, and packaging is then carried out. Radiation characterisitcs of components and circuit elements must be investigated to assure compatibility with their intended use. The most common, routine circuit should be investigated objectively. Switches, relays, brushes, and any other contractor type devices deserve special scrutiny. Relocation of subassemblies or major components, changes in packaging and weight, and revision of excitation levels or frequencies are examples of changes which might be recommended as a result of EMC problems uncovered. When problems are detected, if they cannot be eliminated at the source, their effects must be nullified or restricted to make them harmless, by shielding, for example. Electromagnetic shields must be carefully designed not only to assure effectiveness, but to minimize weight, space, and ventilation problems.

During prototype fabrication, all engineering design information must be incorporated into the hardware. Special fabrication or assembly techniques may be required to make leak-proof RF gaskets, for example.

As prototype hardware evolves, evaluation for EMC should be conducted on a priority level similar to that for major environmental evaluations. As soon as practicable, original predictions and system EMC budget allocations should be reviewed and updated as necessary. EMC suppression and reduction techniques are applied to alleviate any design shortcomings discovered. Corrections made at this stage can save considerable money and time over design changes incorporated as an after-the-fact fix at a later date.

On current and past projects, a veritable flood of production delays and flight qualification problems can be attributed to difficulties involving electromagnetic compatibility. The dense electronic packaging of an aircraft subjects each component of each subsystem to a wide spectrum of interference. An electric or magnetic field is radiated by everything carrying an electrical current, and every device that uses electronic circuitry is susceptible to that radiation to some degree. Unwanted interactions can occur not only between components on the subsystem level, but between the system and its environment. All possible interference coupling paths must be investigated. It is not merely a matter of indicating that a signal must be routed between known points, but of analyzing all possible radiation and conduction paths that might create an interference problem.

The impact of EMC problems on program costs and scheduling can be greatly reduced when competent EMC personnel who have the complete backing of management are called in at the inception of the project. Attempts at after-the-fact fixes in all cases are much too expensive to even consider risking a

project that neglects or minimizes the EMC requirements until the final phases of the program.

Following is a summary of facts pertinent to a full-scale EMC program:

1. EMC specifications and standards must be tailored to each operational requirement to ensure that a system will be compatible with its operating environment.

2. Many costly program delays and costly mission aborts have been traced to electromagnetic incompatibility.

3. It is important to properly interpret the environmental conditions and design for electromagnetic compatibility.

4. Und~~ most circumstances, it is impractical to consider after-the-fact fixes as an acceptable approach to system compatibility.

It is therefore concluded that an EMC program is an essential part of any project in which electronic/electrical equipment and devices are used.

EMC Analysis and Control During System Evaluation

After hardware design has been crystalized and prototype evaluation has been completed, full-scale EMC evaluation should be conducted on the first production lot to verify that all corrective actions recommended during development have reached the working drawings at the shop level and also to uncover any changes resulting from handling and fabrication during production. Because EMC is primarily engineered into the product, a thorough evaluation at this point should constitute the last major design review and verification. Thereafter, a limited sampling of each regular production item is desirable and required to ensure that quality control factors and minor changes do not result in deterioration of EMC.

Once each of the several equipments has been qualified according to equipment EMC specifications, the ultimate test of compatibility is to integrate them into a complete system and observe its performance in the field environment. While the electromagnetic environment of the system can probably be simulated reasonably well if it is known, this expedient will usually not be completely satisfactory because of schedule and instrumentation considerations. The various subsystems sometimes undergo evaluation at about the same time so that EMC characteristics of the complete system may not be known before delivery. Nevertheless, some evaluation of the integrated system in its simulated environment is possible and should be undertaken before field evaluation.

Field evaluation for EMC can involve elaborate and expensive set-ups. Extensive cooperation between co-contractors and subcontractors is necessary and desirable since deficiencies may often be corrected either by suppressing the source of the undesirable radiation or protecting the affected equipment or both. The assistance of the equipment manufacturer should be requested any time a modification or alteration of his equipment is being considered.

EMC Analysis and Control During Production

Once the engineering development models of the system being produced have qualified in terms of electromagnetic compatibility, EMC analysis and test

requirements become less elaborate for the production models. However, the need continues. Random samples of items supplied by vendors and subcontractors, as well as those fabricated in-house, should be subjected to qualification testing to assure continued compliance with EMC standards. A change in the vendor supplying a particular part can lead to the development of an EMC problem that did not exist before the change.

An EMC quality assurance test is required as part of the acceptance test to be conducted on each completed model to verify that compatibility has not been degraded by the construction methods or materials used. Because the most likely trouble points have been found during the system evaluation tests, these points can be used to plan the quality assurance tests.

EMC Analysis and Control During the Operational Phase

The effectiveness of EMC control measures applied to an aircraft is given its ultimate test when the aircraft is turned over to the operating forces. Tests are no longer conducted under synthetic conditions, the aircraft is subjected to operation under actual conditions and in proximity to other systems.

Once the aircraft is placed in operational status, electromagnetic compatibility becomes the responsibility of the military personnel who operate and maintain the aircraft. However, the operating organization continues to receive guidance and support from other elements of the Navy, and from contractual services provided by the manufacturer. Free-flowing channels of communication for exchange of information on problems and solutions are essential elements of support. Chapter 19, addressed to operational, maintenance personnel, covers this subject in more detail.

Operational aspects of EMC control are divided into two related parts: hardware problems concerned with generation of spurious energy and the susceptibility of victim devices; and operating problems concerned with frequency spectrum occupancy and congestion by functional energy essential to the operation of devices that are part of the aircraft system or part of the environment in which the aircraft operates, or both.

As part of the contractual negotiations, a production package is required of a contractor. This package includes engineering drawings, manufacturing specifications, layout plans, and technical data developed during the production phase. From this large quantity of detailed information, the cognizant systems command develops the technical documentation for personnel who operate and maintain the system. To avoid degradation of EMC attributes of the system, and to take full advantage of operational modes and characteristics contributing to improvement of compatibility, the production package and the resultant maintenance manuals and operating instructions should contain information on EMC analysis and control related to the system. For example, a powerplant mechanic or an aviation electrician is not likely to understand fully the characterisitcs of shielding and bonding measures used on the engine, or on electric lights, motors, or circuit breakers, and unless his attention is directed specifically to an EMC problem, he may allow deficiencies affecting EMC to go unnoticed. The pilot may not understand that it is desirable to use the low

position of his IFF, radar or communications system when his aircraft is near the task force in order to improve resolution, reduce congestion and otherwise contribute to EMC by minimizing the strength or number of radiations generated.

Operating considerations for EMC include such things as arranging frequency assignments so that systems are sufficiently separated, or so that one system is not placed on a critical harmonic or image frequency of another system. The mission profile is also affected by EMC in terms of scheduling the time a system is to be flight-checked, placed in standby, or operated.

EMC CONTROL ORGANIZATION

The fourth objective, control and guidance of the EMC program, is served by the EMC Control Plan, together with the Electromagnetic Control Advisory Board (EMCAB) formed according to its provisions. The EMC Control Plan is a positive statement of management policies; it informs each department head, each engineer, each subcontractor, and the procuring activity of the work effort, the emphasis, and the design guidelines that are to be used to ensure that interference problems do not develop late in the program, when schedule slippages and cost overruns will be most detrimental to the overall program.

The first function of the EMC control organization is to plan a program that produces consistent EMC analyses of all critical components, subsystems, and operational sequences involved in the overall system capabilities and mission envelope. These analyses and estimates should be systematically reviewed and updated throughout each state of a system's development and be based on the best design, engineering, and test data available. In particular, overall system EMC estimates, including supporting confidence level data, should be a formal product of such planning.

The EMC control organization should also provide clear definitions of specific research and development design, engineering, and testing problems that need to be solved to meet the electromagnetic compatibility goals for the system and mission as required by policy or by economic or other considerations; and, conversely, clear definitions of the EMC goal trade-offs which might be required by changes in economic, scheduling, or other constraints on the program.

The EMC control organization should be a part of a structure of managerial controls and procedures, at all organizational levels, that will tend to minimize mission, organizational, or other bias in attaining the goals set forth in the control plan.

EMC engineering and management may be considered an accessory or service function. It develops data and operational patterns for assisting the other responsible elements of the overall program to determine what is technically attainable, and how to assure attainment of systems and mission electromagnetic compatibility.

EMC EDUCATION AND TRAINING

The fifth objective of the EMC program is the education and indoctrination of management, design, test, operation, manufacturing, and maintenance

personnel to an awareness of EMC requirements and principles. The indoctrination it provides can reduce the total development time and costs of avionic equipments and systems. Good basic understanding of the policies, directives, problems, and solutions is the best insurance that the EMC program will be properly interpreted and carried out.

The educational program can be accomplished most effectively through overall training starting with management aspects and continuing through the technical phases. The basic goal of EMC education is to transmit knowledge of such concepts as RFI, EMI, susceptibility, or compatibility, to all levels of operations and management. If it can be made clear that basic electrical/electronic theory used daily by the design or development engineer is the same theory used for electromagnetic interference control, the training program can be considered a success. The only difference is that the EMC engineer examines most critically the undesirable effects of an electronic phenomenon, whereas the designer is concerned with the useful portion of this same phenomenon.

The scope of the training program may range from a comprehensive indoctrination of all responsible management and operational personnel regarding policies, procedures, milestones, and goals, to a formal EMC educational and training program. Production personnel should be indoctrinated in the proper assembly procedures to meet specified EMC design criteria. The important considerations are that all appropriate organizational elements participate in the program, that sufficient time be allotted, and that qualified personnel present the subject in understandable terms with the necessary breadth and depth to ensure complete coverage.

NAVY EMC RESPONSIBILITIES

Figure 4-1 shows a simplified organizational structure of the Department of the Navy. Almost every command and office in the Navy Department is affected to some degree by the DoD EMC program, but it is not feasible to discuss all aspects of each. One can recognize the importance of the Bureau of Medicine and Surgery program for investigating biological effects of electromagnetic radiation, the Bureau of Naval Personnel training programs, the action of the Office of Legislative Affairs in gaining authorizations and funding of the EMC portions of various projects, and many others. However, the principal interest of this publication lies in the development, procurement, and operation of electronic systems by operating forces under the Chief of Naval Operations.

SECNAV Instruction 2410.1B of 21 June 1967 designated the Chief of Naval Operations (CNO) as the executive of the Department of the Navy in matters pertaining to EMC, and directed CNO to take the actions necessary to achieve electromagnetic compatibility within the Navy, and between the Navy and other users of the electromagnetic spectrum.

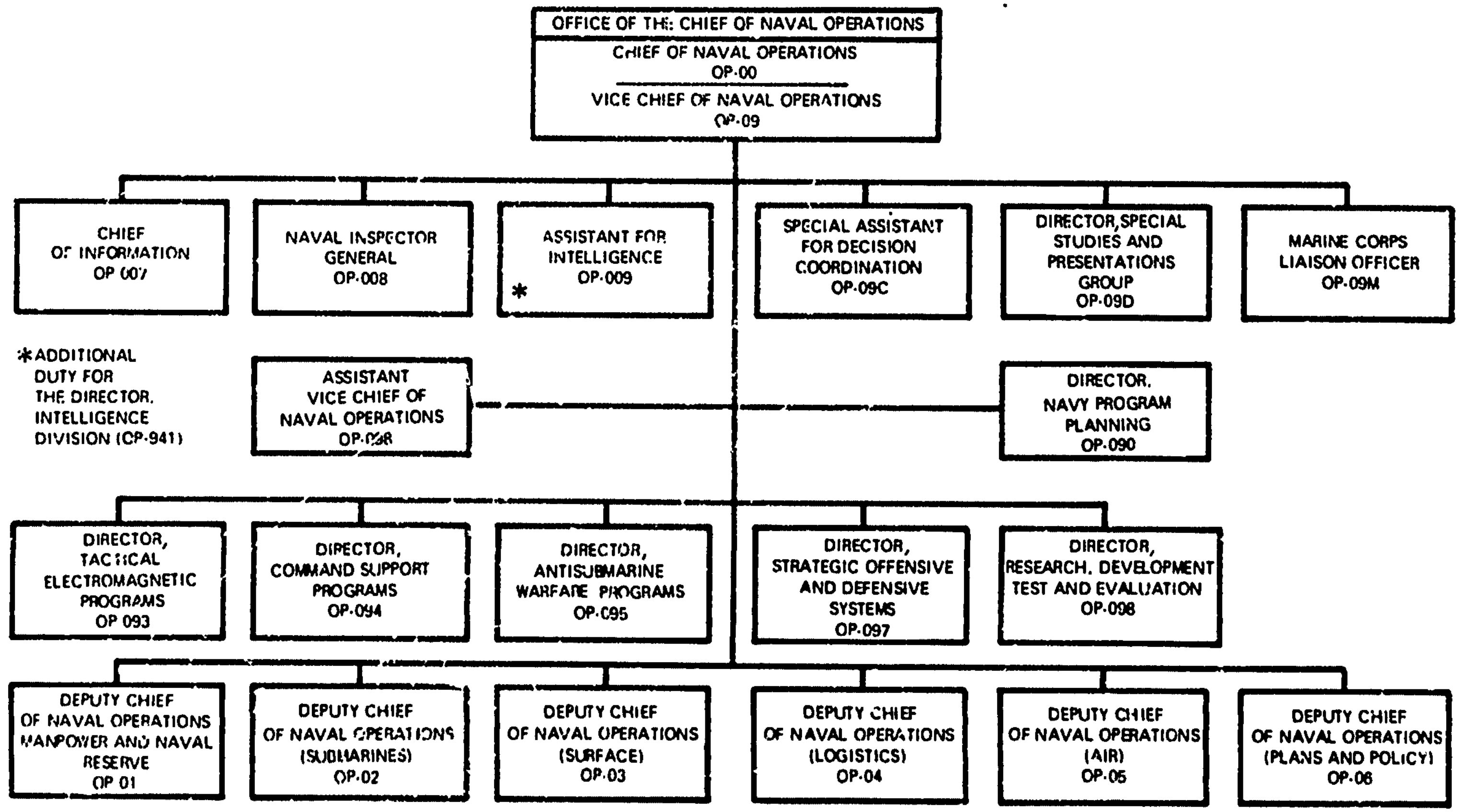


FIGURE 4-1 SIMPLIFIED ORGANIZATIONAL CHART, U.S. DEPARTMENT OF THE NAVY

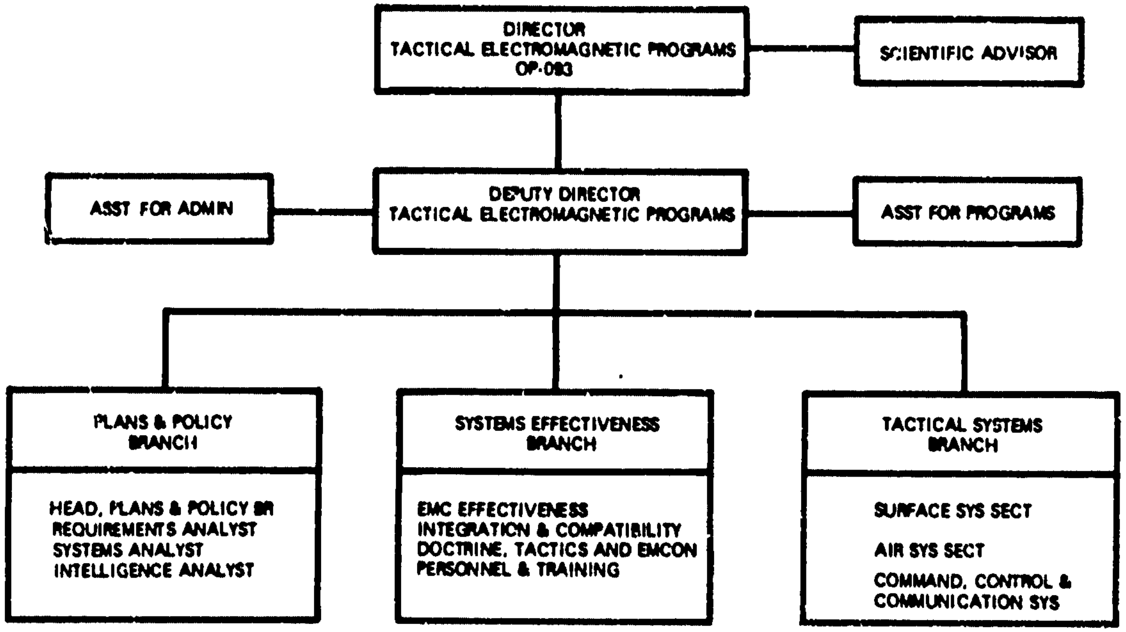


FIGURE 4-1 (CONT'D) SIMPLIFIED ORGANIZATIONAL CHART, U.S. DEPARTMENT OF THE NAVY

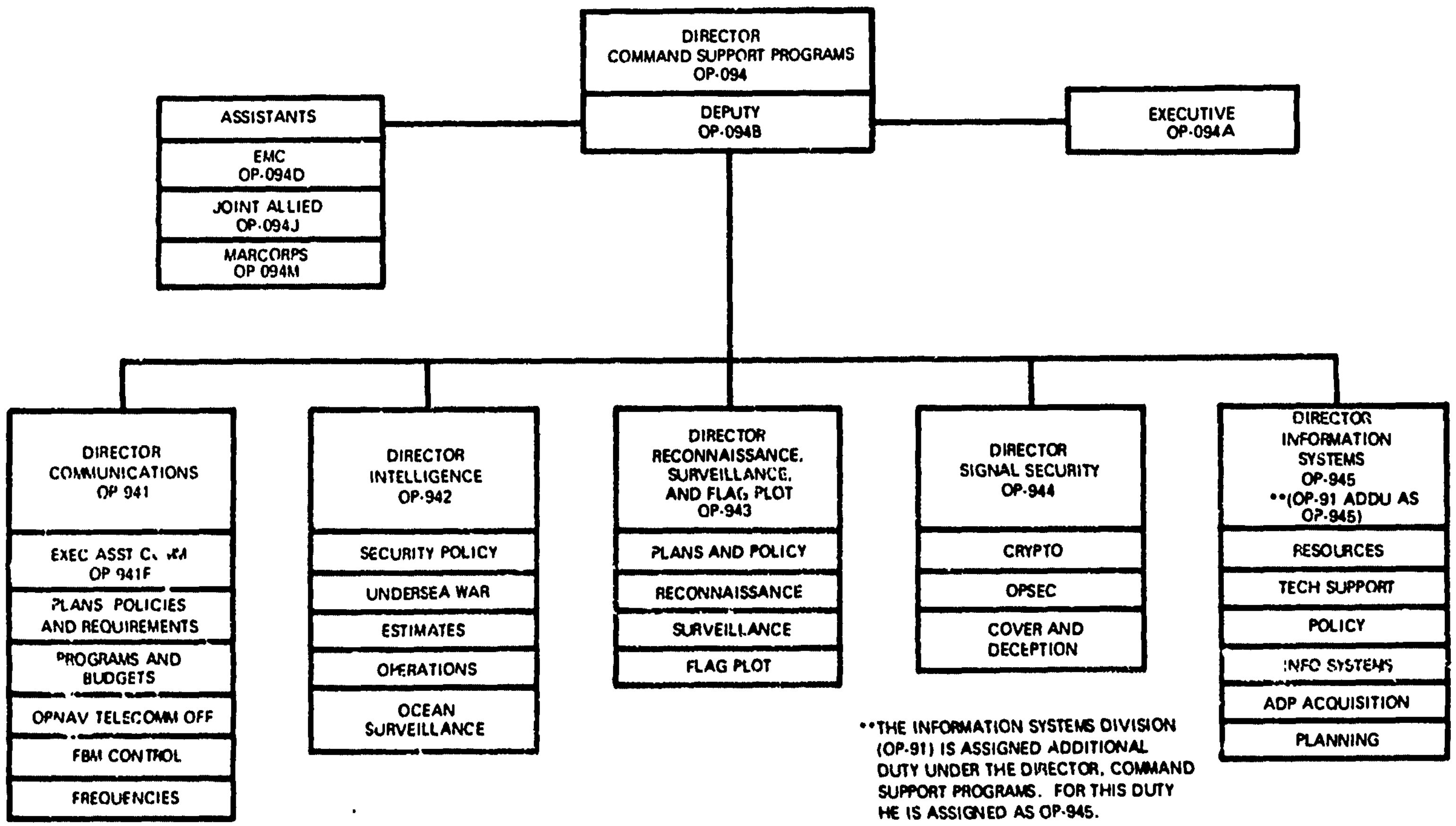


FIGURE 4-1 (CONT'D) SIMPLIFIED ORGANIZATIONAL CHART, U.S. DEPARTMENT OF THE NAVY

The Chief of Naval Operations (CNO) in turn assigned the Director, Command Support Programs responsibility for the direction and coordination of EMC matters within the Navy. CNO also directed that certain actions relating to EMC be taken by the Vice Chief of Naval Operations, the Chief of Naval Material, the Commandant of the Marine Corps, and the Chief of Naval Research. In keeping with his EMC responsibilities, CNO updated the mission and membership of the Navy Frequency Allocation Advisory Board (FAAB) and established procedures for the collection and submission of spectrum signatures for the DoD Electromagnetic Compatibility Program.

The Commander, Naval Electronic Systems Command (NAVELEX), acting as agent for the Chief of Naval Material (CNM), is responsible for policy direction and overall coordination of the EMC program within the Naval Material Command. The Commander, NAVELEX, serves as principal advisor to CNM for review of EMC features of components, systems, Technical Development Plans (TDPs), specifications, and criteria for adequate EMC funding. In this capacity, the Commander, NAVELEX, provides administrative support for the Naval Material Command EMC Executive Committee. The committee advises and assists CNM in overall program planning, coordination, and review of EMC actions within the Naval Material Command, and liaison with CNO and other interests in regard to EMC.

DEVELOPING, DISSEMINATING AND ENFORCING SPECIFICATIONS AND STANDARDS

The Vice Chief of Naval Operations is responsible for developing Navy requirements for interference elimination to be applied during design, construction, and installation of communications-electronics/electrical equipments for aircraft, weapons (including missiles), surface, subsurface, aerospace, and shore electronics systems. His responsibilities include development and maintenance of a coordinated DoD plan to provide a complete range of EMC standards including those for prediction, measurement, and validation of EMC. This plan is closely coordinated with the Department of the Army planning efforts in measurement techniques and instrumentation.

The Chief of Naval Material (CNM) has the responsibility within the Navy for developing and improving engineering standards and criteria for interference elimination in the design, construction, installation, and operation of Navy communications-electronics equipments.

The commander of each systems command and each project manager designated by CNM is responsible for ensuring that coordinated EMC specifications, engineering standards, and other criteria are enforced within his organization.

Cognizant engineers and managers of procurement or development projects are responsible within their systems command for ensuring that all necessary EMC/EMI requirements, including the latest revisions of the specifications, are incorporated in all equipment/system contracts. They are also responsible for ensuring that requests for deviations in the EMC area are fully investigated. It is Navy policy to grant deviations only when strong justification can be provided.

EMC RESPONSIBILITIES IN PROCUREMENT AND LOGISTICS SUPPORT

The Vice Chief of Naval Operations is responsible for direction in the R&D aspects of electromagnetic compatibility, both within the Navy and with respect to the exchange of information with other DoD components. He is also responsible for ensuring that Specific Operational Requirements (SORs), Advanced Development Objectives (ADOs), Proposed Technical Approaches (PTAs), and Technical Development Plans (TDPs) developed by the Navy, and concerned with C-E equipments and electrical devices, provide for electromagnetic compatibility. His office provides membership on intra-departmental and DoD Working/Study Groups concerned with R&D aspects of EMC.

The Chief of Naval Material has the responsibility for ensuring that electromagnetic compatibility is achieved in the material phases of design, development, procurement, installation, and operation of C-E equipments within the Navy. To this end, his responsibilities include ensuring that adequate funding is requested to perform the tasks assigned, including Navy support for ECAC. To prevent expenditures for electronic equipments which lack provision for frequency assignment, CNM has established safeguards to ensure that frequency assignments are made before any development or procurement of electronic equipments. Pursuant to this aim, the Chief of Naval Operations (Communications) provides CNM with copies of all completed frequency assignment actions, whether approved or disapproved.

The commander of each systems command and each project manager assigned by CNM is responsible for ensuring that EMC measures are applied to the electronic/electrical equipments and systems under his material support responsibility.

Each systems command project director is responsible for supplying information for the incorporation of EMC requirements into GORs, SORs, TDPs, Request for Proposals (RFPs), and Request for Quotations (RFQs) under his cognizance. He also provides EMC representation to the Naval Material Command EMC Executive Committee and associated subcommittees for overall NAVMAT program planning, coordination, and for liaison with CNO and other interested parties in regard to EMC. He is additionally responsible for ensuring that adequate funding is requested to meet the above responsibilities.

Cognizant project engineers and managers are responsible for ensuring that all requirements or changes to requirements (such as SORs and TDPs) involving C-E systems or equipments which may affect the electromagnetic compatibility of a system are reviewed by the EMC section of the office of the project director. Cognizant project engineers and managers are further responsible for ensuring that specific contract data items such as applications for frequency allocations, EMC control plans, EMC test plans, and EMC test reports are included on the Contract Data Requirements List, DD Form 1423. The purpose of these requirements is to control equipment/system electromagnetic emissions and susceptibilities and intrasystem and intersystem interference effects so as to bring them within acceptable limits, thereby achieving electromagnetic

compatibility. Necessary action shall be taken to ensure that these requirements are met, including establishment of an Electromagnetic Compatibility Advisory Board if required by the procuring activity.

RESPONSIBILITY FOR FREQUENCY ALLOCATIONS AND SPECTRUM SIGNATURES

Much Department of the Navy communication/electronic research and development work is conducted, under contract, by industry. In such instances, it is the responsibility of the contracting command or office to maintain sufficiently detailed liaison with contractors to ensure that frequency allocation applications are submitted to the Chief of Naval Operations (CNO) in accordance with the procedures set forth in the basic instructions. If the cognizant command or office does not maintain active supervision of the selection of radio frequency bands by the contractor, a clause will be included in the contract to require coordination with the cognizant command or office of all measures that will affect the ultimate allocation of a radio frequency.

Responsibility for the procurement, assignment, and protection of all radio frequencies used by the Department of the Navy rests with the Chief of Naval Operations, who acts through the office of the Director of Communications. The responsibilities of the Director of Communications include the following:

1. Ensuring that procurement, assignment, allocation, and protection of radio frequencies within the Department of the Navy is effected to obtain maximum operational compatibility within the Navy and Marine Corps, and between the Navy and Marine Corps and other users of the radio frequency spectrum.

2. Establishing Navy requirements for collection of spectrum signatures, environmental data, and test and measurement support in furtherance of the DoD Electromagnetic Compatibility objectives.

3. Providing membership on the Interdepartmental Radio Advisory Committee (IRAC), Joint and Combined Frequency Panels (JFP) and Working/Study Groups concerned with the operational aspects of EMC.

The functions of the Director of Tactical Electromagnetic Programs (OP-093) are discussed in Chapter II.

The commander of each systems command and each project manager designated by CNM is responsible for ensuring that spectrum signatures are obtained and submitted for all electronic equipments, are required, and that ECAC projects are properly supported.

When research and development is conducted under contract by industry, it is the responsibility of the cognizant development agency to maintain close surveillance of such activities to ensure that applications for Navy frequency allocations are submitted when appropriate. Before submitting a frequency allocation application, the developing or procuring agency must consider, as far as possible, all other equipments and systems that must operate in conjunction with systems involved in the application. The purpose of this action is to ensure that obvious interservice EMC problems are resolved readily.

Each cognizant systems command division director is responsible for providing guidance and assistance to engineers and project teams are required in the preparation of Frequency Allocation Application, DD Form 1494, and in review of this form before its submission to CNO. His responsibilities include reviewing the Electromagnetic Compatibility Program spectrum signatures provided by Navy field activities or by contractors for adequacy and submitting them when technically acceptable. He is also required to provide members to the Navy Department Frequency Allocation Advisory Board (FAAB) in accordance with pertinent CNO instructions.

Cognizant NMC project engineers and managers are responsible for ensuring that, whenever possible, the equipments being designed are tunable over the complete frequency band allocated for the type of equipment They are required to prepare and submit frequency allocation applications in accordance with applicable references and ensure that spectrum signatures are obtained and submitted for all electronic equipments as required. Spectrum signatures shall be coordinated with the cognizant systems command division director to determine if the spectrum signature data complies with requirements.

The cognizant naval plant representative monitors required spectrum signature measurements to assist the contractor in complying with contract requirements and reviews and makes written recommendations as to whether to approve or disapprove spectrum signature data submitted by the contractor.

Laser Operations

Laser operations are conducted in the electromagnetic spectrum above that portion currently defined as the radio spectrum–3 Hz to 3000 GHz. Although specific frequency assignments are not required for laser operations, it is necessary to obtain frequency allocations for telecommunication lasers and to report non-telecommunication laser operations. In the interest of prudent frequency management, laser operations must be reviewed to ascertain the trend in laser developments and to assist in determining whether future allocation action will be required in the electromagnetic spectrum used by such devices. Accordingly, the Director, Telecommunications Policy, Executive Office of the President, has requested that all laser operations for telecommunication, and all laser operations for other than telecommunication that could result in harmful interference to telecommunication laser operations, be reported to the Interdepartment Radio Advisory Committee (IRAC).

Applications for frequency allocation for telecommunications laser developments should be submitted to the Chief of Naval Operations (OP-941F) according to the provisions of OPNAVINST 2410.11E of 6 April 1967 or the applicable directives for other departments and agencies. Non-telecommunication laser operations should be reported before they begin.

Contractor Frequency Applications

A tri-service panel on the new Joint Military Procedures for processing contractor frequency assignment applications recently adopted joint procedures

as follows:

1. Contractors having a need to operate a C-E device in the radio spectrum under a valid military contract must submit a frequency assignment application for approval before operation of the device.

2. Contractors who have a military department plant representative assigned, either military or civilian, or who are conducting operations at a military installation, will request assignment of the frequencies required from the military department representative or instalation commander as appropriate. The request would be submitted through those channels directed by the appropriate military department administering the contract. Frequencies will be coordinated and assigned in accordance with departmental regulations.

3. Where the frequencies will be used in an area under the cognizance of an MCEB-designated military Area Frequency Coordinator, the AFC will be included in the coordination channel.

4. Contractors having contracts from more than one military department for the same or similar operation will request frequency support only from one military department. Normally, this will be the military department from which the military plant representative is assigned.

5. If radio operations are required under a valid military contract and operations are not under the control of a military plant representative or a military commander, the contractor must apply to the Federal Communications Commission for a station license. The FCC will effect coordination with the cognizant military department in regard to the need for the requested authorization. To facilitate processing of the request, the cognizant military department should be provided a copy of the contractors request to the FCC.

6. For expeditious handling of contractor frequency requests, complete information must be submitted. Requests will be reviewed to ascertain if approval for frequency allocation has been obtained and if the requirement can be satisfied from existing command frequency resources.

7. Normally, frequencies provided through this process will be assigned on a non-interference basis to established radio services.

8. Frequencies required for contractor plant operations which cannot be directly associated with a current military contract cannot be provided through this process. Such requirements must be processed through the FCC using current FCC procedures.

DEVELOPMENT OF DATA ACCESS, ANALYSIS, AND PREDICTION

The Director of Communications is responsible for providing, verifying, and updating the various categories of Navy and Marine Corps environmental information maintained in the Electromagnetic Compatibility Analysis Center (ECAC) files. The Director is also responsible within the Navy for assignment of analysis tasks to ECAC to investigate electromagnetic compatibility problems among existing or projected communications-electronics equipments.

The Chief of Naval Material (CNM) is responsible for achieving the capability to simulate weapon (missile), aircraft, surface, subsurface, aerospace,

and shore electronics environments and to predict potential interference. The services of ECAC are available.

The commander of each systems command has, for projects under his purview, the responsibility for ensuring that realistic predictions relating to electromagnetic environment and mutual interference among systems and equipments are made during the early phases of development that they are kept up to date during development, and that equipments are tested in simulated electromagnetic environments prior to commitment for quantity procurement or installation.

Each cognizant systems command division director is responsible for establishing, in collaboration with other Naval Material Command elements in which a common electromagnetic environment exists the capability to simulate and predict electromagnetic interference involving systems and equipments under his material support responsibility. He is responsible for proper support of ECAC projects and makes maximum use of ECAC capabilities.

RESPONSIBILITY FOR EMC CONTROLS

The Chief of Naval Operations has the responsibility, during the acquisition, installation, and operation of naval material of assuring contractual adherence to specifications and standards pertaining to interference elimination and control in communications-electronic/electrical systems of the Navy and Marine Corps.

The Vice Chief of Naval Operations (OP-09) is responsible for advising the Deputy Chief of Naval Operations (Submarines) Deputy Chief of Naval Operations (Surface) and the Deputy Chief of Naval Operations (Air), as appropriate, of potential electromagnetic incompatibilities and interferences during the development of equipments and for providing reasonable courses of action to overcome the problems.

Each cognizant systems command division director is responsible for providing assistance and direction to project managers in establishing an Electromagnetic Compatibility Advisory Board (EMCAB) for monitoring each new major system being procured for naval use. Cognizant managers and engineers are responsible for ensuring that the design of all systems equipments, and components under their cognizance is directed to the maximum practical degree permitted by the state of the art to engineering compatible systems.

The Naval Plant Representative for each project is responsible for evaluating EMC Control Plans, EMC Test Plans, EMC Test Reports, and proposed deviations submitted by contractors and for preparing written recommendations for approving or disapproving these documents, including reasons for disapproval and changes required before resubmitting for approval. His responsibilities also include working with the contractor in resolving EMC problems. To carry out these responsibilities most effectively, the Naval Plant Representative is usually a member of EMCAB.

RESPONSIBILITY FOR EMC TESTS, MEASUREMENTS, AND EVALUATION

The Director, Command Support Planning, is responsible for determining systems electromagnetic incompatibilities and interferences by analysis and complete platform environmental tests. In keeping with this responsibility, he advises the Vice Chief of Naval Operations (OP-09), the Deputy Chief of Naval Operations (Air), and the Commandant of the Marine Corps, as appropriate, of any EMC problems found to exist and solves the problems.

The Chief of Naval Material establishes and maintains the test and evaluation capability necessary to achieve electromagnetic compatibility. Under his direction, the commander of each systems command ensures that the capability is available to verify electromagnetic compatibility of systems, equipments, and devices under his responsibility.

To assist the Chief of Naval Material in EMC matters, the Naval Electronic Systems Command (NAVELEX) has established (and chairs) an NMC EMC Executive Committee composed of representatives from NAVAIR, NAVELEX, NAVFAX, NAVORD, and NAVSHIPS. The NMC EMC Committee provides advice and assistance to CNM on all material aspects of the Navy EMC program, which has been defined in NAVMAT INST 2410.2 as including but not limited to:

1. EMC performance standards, specifications and other criteria
2. Electromagnetic environment simulation and interference prediction
3. Frequency allocations
4. EMC measurements including spectrum signatures, and instrumentation
5. Use and support of ECAC
6. EMC education

Cognizant systems engineers and managers coordinate with, and support, the Division Director during all phases of Navy Preliminary Evaluation, Board of Inspection and Survey (BIS) Trials, and all other tests, evaluations, and trials up to final delivery of the product for operational use. These responsibilities require ensuring that EMC is given continuous consideration, that all EMC contractual requirements are met, and that a maximum degree of EMC is attained in the delivered product.

The cognizant Naval Plant Representative of each project is responsible for monitoring all required EMC testing to validate their completeness and accuracy.

The Board of Inspection and Survey, Washington, D.C., with offices and facilities at the Naval Air Test Center, Patuxent River, Maryland, is responsible for conducting acceptance trials for Navy and Marine Corps aircraft.

RESPONSIBILITY FOR EMC EDUCATION

The Chief of Naval Material is responsible for providing for the training of Navy and contractor personnel in the detection and elimination of interference

during design, development, operation, and maintenance of Navy materiel.

Each cognizant systems command division director is responsible for the indoctrination and training of Navy and contractor personnel in the various aspects of EMC pertinent to the equipment and systems under his material support responsibility as required by the commander of each systems command.

RESPONSIBILITY FOR EMC FIELD SUPPORT, OPERATION AND MAINTENANCE

The Chief of Naval Operations is responsible for the conduct of service tests and operational evaluations of C-E equipments and systems used by the Navy. These tests and evaluations are performed to ensure EMC in typical operational environments, and to establish confidence in analyses and predictions made during the development and production phases.

The Vice Chief of Naval Operations (OP-09) is responsible for establishing procedures for detecting, reporting, and solving operational EMC problems, and for providing the necessary feed-back to other offices concerned with standards, education, and analysis of EMC. To serve as a focal point in meeting this responsibility, a Director for Tactical Electromagnetic Programs has been designated to develop and promulgate objectives within the Department of the Navy relating to EMC and to ensure that communications and other electronic devices used by the Department of the Navy perform satisfactorily under operational conditions.

REVIEW OF EMC PROGRAM GOALS

SYSTEMS PERFORMANCE EFFECTIVENESS

Effective performance of Navy systems in Fleet use is essential to the success of Navy operations. During the past few years, useful techniques have evolved from an extensive effort to improve the effectiveness of Fleet systems.

The Systems Performance Effectiveness (SPE) Program developed by the Naval Material Command has been promulgated by the Navy Systems Performance Effectiveness Manual, NAVMAT P3941-A. Systems performance effectiveness is defined in this manual as, "A measure of the extent to which a system can be expected to complete its assigned mission within an established time frame under stated environmental conditions." This definition establishes the scope and content of the SPE program. The terms clearly indicate that environmental conditions and time are integral parts of the SPE concept.

Current and projected military strategic studies indicate that threats are becoming more complex, decision time is reduced, tactical decisions are more critical, and available reaction time is reduced, the overcoming of which requires increased complexity in the systems that form a weapon system capability. More complex systems in turn generate greater technical and operational problems.

Consequently, achievement of satisfactory performance in the Fleet has challenged the ingenuity of the scientist, engineer, and technical manager, and has influenced trends in all engineering and management disciplines. The goal of any weapon system development is to produce a system that can be operated and maintained to the full extent of its design capability.

In this subsection, the principal areas of concern for Systems Performance Effectiveness relevant to EMC include:

1. Reliability, normally expressed in terms of time between parts failures.

2. Maintainability, normally expressed in terms of time required to return the system to service.

3. Capability, normally expressed in such terms as radius of action, payload, detection range, communication distance, and tracking accuracy.

4. Compatibility, normally expressed as the permissible degree of degradation of performance caused by concurrent operation of multiple systems or subsystems in an operational environment.

The above SPE areas may pose mutually conflicting requirements. For example, increased capability may call for increased power, which in turn may bring about greater heating and consequent reduced reliability, along with greater interference levels which reduce compatibility. Increased compatibility may call for more stringent shielding and filtering, which may reduce both accessibility for maintainability and ventilation needed for best reliability.

An important stage in the development of effectiveness criteria is estimating the resource constraints for each system by the project manager. There are three distinct, logical divisions of this function.

First, absolute upper limits are placed on the specified constraints. For example, the program may have a two-year lead time as an absolute requirement, or it may have certain size and weight constraints because of payload considerations. Only systems that satisfy these requirements can become candidates for development or procurement.

Second, the constraints are treated as design parameters, and the impact of each is measured where possible in terms of performance capability and time-dependency. For example, employment of technicians in higher skill brackets reduces downtime and affects time-dependence; provision of ample lead time reduces development risk, allows the use of advanced technology, and therefore affects performance capability.

Third, the constraints are treated as quantitative attributes of the system in their own right, and specific values are estimated in terms of time and cost for each design.

During acquisition the role of SPE measures is to enable the program manager to restructure the allocated goals to the system level, thereby allowing system decisions to be made by higher management. Dynamic life cycle management and Integrated Logistics Support then become practical goals. SPE techniques are intended to aid the project manager in decision-making by presenting him with organized information in a visible form, and to assist him in assigning task priorities by highlighting critical areas within his project. Systems

performance effectiveness is not a replacement for managerial judgement, but it supplies a basis for better and more timely decisions.

During the earlier stages of development or procurement, system functions are quite broadly defined. The gross functions are progressively structured as groups of subfunctions, each with its inputs and outputs. Structuring continues until the candidate system has been defined. This approach permits comparative evaluation of competing candidate systems, regardless of their relative stage of evolution.

The cost-effectiveness analysis of a proposed system is based on a two-part cost estimate associated with each function in the SPE model. One estimate covers the cost of acquisition; the other covers the cost of use or ownership. The former includes RDT&E costs, prorated over the anticipated production quantity, as well as any production and installation cost. The latter includes all operating, maintenance, and support costs of the system. These costs can be used in making trade-off analyses, or they can be aggregated and associated with the SPE index and used as partial determinants in preferred-system selection. Other partial determinants useful in preferred-system selection are comparisons of system performance effectiveness indexes with manpower and leadtime requirements.

The preferred-system definition and the critical system performance effectiveness parameters are incorporated into a Request for Proposal (RFP), which is transmitted to contractors as a guide for proposed approaches to contract definition. In addition to providing guidance for the contractors, defining critical system performance effectiveness parameters provides criteria for evaluating contractor proposals.

CONTROL PLAN EFFECTIVENESS

An EMC Control Plan is most effective when it is implemented at the management level rather than at the interference testing level. EMC achieved through a test-and-fix program followed by an after-the-fact rework and consequent retest can seriously damage a production schedule. Time and funds expended on alterations and modifications are wasteful. They cannot be scheduled accurately, and their conclusion is seldom satisfactory.

The EMC program is governed and directed by the EMC Control Plan, which establishes the EMC control philosophy for the entire project. It determines the interference measurement and control techniques that will be used, and it provides detailed procedures for meeting EMC design specifications. The EMC Control Plan is based on three sets of inputs: operational and environmental data, applicable military and contractor specifications, and preliminary design and prediction data.

Operational and environmental data should be furnished by the procuring activity, but this is not always possible. The environment in which the system under development must operate often depends upon other equipment that is being built simultaneously by other contractors. Hence this input must be continuously revised and updated. The procuring activity is expected to provide information on frequency allocations, power levels, mission envelope, and

operating environment, and to specify contractual requirements and test methods to achieve the desired level of compatibility.

Military and contractor specifications to be applied to the contract are usually well known, but they must be interpreted for the specific task at hand. The EMC Control Plan implements these specifications according to contractual requirements or waivers and special situations and requirements relating to the equipment under development.

Preliminary design and prediction data depends upon analytical modeling techniques, which may contain technical and operational estimates. For example, the shape, amplitude, duration, and repetition rate of the modulator pulse in a radar system being planned can be estimated within a few percent of its final values. Similar estimates can be made for most other high-powered signals. Usually, important wave shapes in a system have been defined in the proposal stage. Preliminary design information, supplemented by prediction techniques, can be developed into data on transients, impedances, cable coupling, frequency responses, emissions, and susceptibilities.

The specific inputs produce an EMC Control Plan adapted to the peculiarities of the system under development. The control plan, in turn, provides inputs necessary for the detailed specifications to be used on the system, such as specifications for grounding, bonding, shielding, wiring and cabling, filtering and suppression, interference limits, and compatibility requirements. The EMC Control Plan also contributes inputs for other requirements such as system performance, reliability, quality control, and manufacturing specifications and procedures.

Performance monitoring for all these specifications is done continuously during design and development of the system. Formal management control is exercised during the periodic design review and manufacturing review sessions held under the direction of project management. Design reviews are not restricted to EMC but are held for system review by the design and development groups, reliability, quality control, mechanical design. These design reviews are usually contractual requirements under the reliability, EMC, or quality control plans

The EMI/EMC test plan, a contractual requirement, is written by the contractor's EMC group and, upon approval by the procuring activity, represents formal demonstrations of system electromagnetic compatibility. Testing should begin at the component and unit levels to predetermine interference limits and tolerances, and progress to electromagnetic compatibility tests to specified threshold safety margins on the subsystem and system levels. These formal tests follow a tightly controlled procedure to ensure absolute trustworthiness of the test results.

For these formalized EMC tests and plans to be of most value, coordination between design engineers and EMC engineers is imperative. Before and between design reviews, the development engineer performs informal development tests. The project EMC engineer must be available to assist during these tests.

Results of the various design reviews are then fed back to the EMC Control Plan, thereby keeping the plan an everchanging dynamic document to benefit

the system under development. Information is also fed back to the prediction function to allow the updating of the prediction model, which generates new interference projections for the EMC control function.

TEST AND EVALUATION

A weapon system undergoes a series of tests and evaluations during its lifetime. The prototype is subjected to ground tests which determine when it is ready for flight. The contractor's test pilots evaluate its airworthiness and ability to perform the mission. The Navy Preliminary Evaluation (NPE) is coordinated with the contractor's tests so that both the contractor and the Navy can be satisfied that the weapon system is ready for the formal Board of Inspection Survey (BIS) trials. These trials determine the operational readiness and include tests that verify that all of the electronic subsystems and the support equipment meet contractual requirements for EMC. When the weapon system has passed the BIS trials, it passes from R&D to operational status.

In passing to operational status the weapon system will be subjected to further test and evaluation during its service life. Representatives from the source contractor, working in conjunction with the Operational Test and Evaluation Force (OPTEVFOR), may conduct tests and evaluations to determine remedial measures for operational deficiencies or for upgrading performance. Alternatively, the weapon system may be returned to the Naval Air Test Center for additional test and evaluation. Corrective action may call for modifications which are made locally by the use of field modification kits, or the weapon system may be returned to the source contractor for rework and modification.

REFERENCES

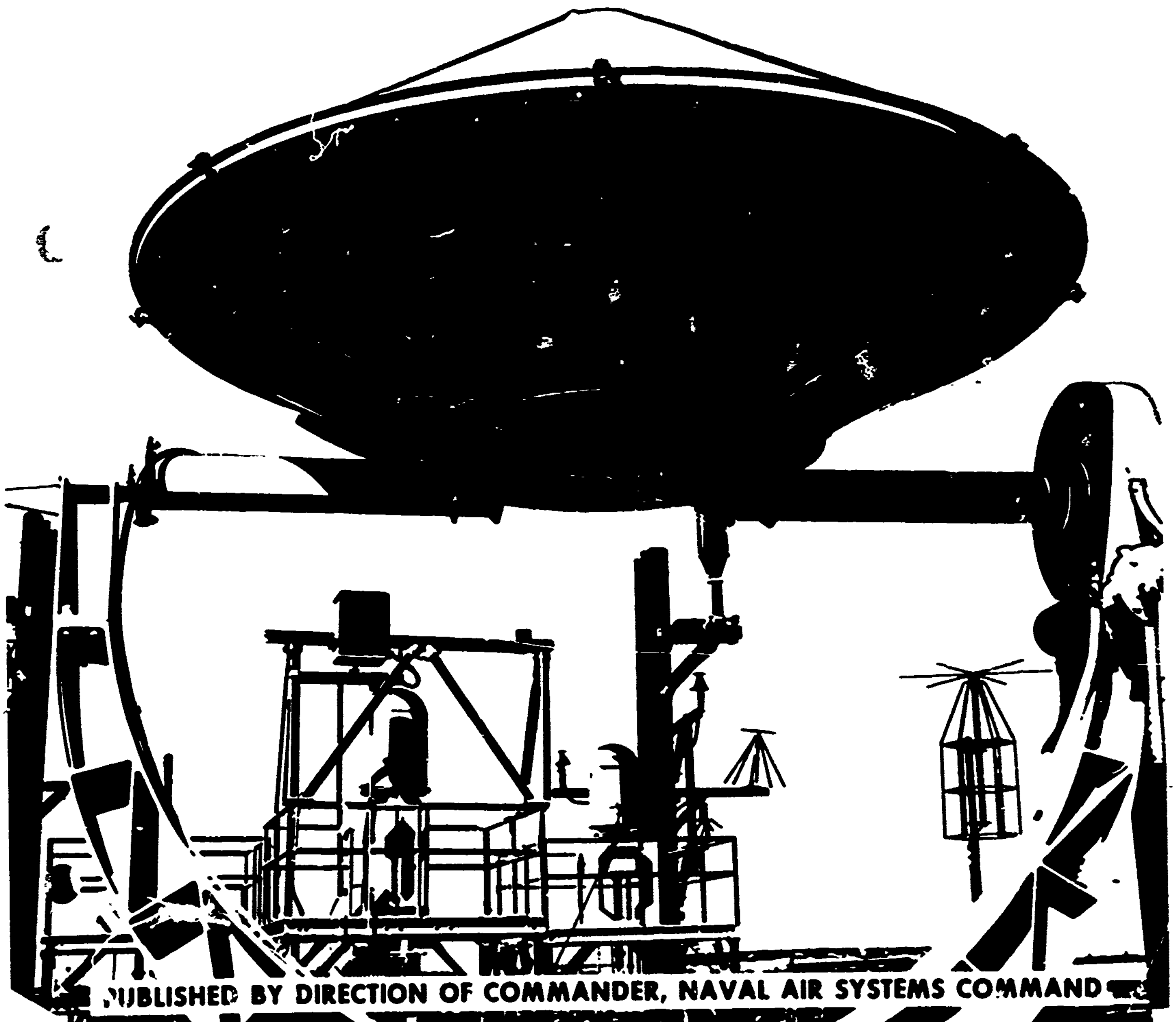
1. *NASA Apollo Program NHB 5320.3 Chapters 2 and 3*
2. *Military Specification MIL-E-6051D*
3. *OPNAV Instruction 2410.31A*
4. *OPNAV Instruction 2410.11E*
5. *NAVAIR Instruction 2410.1A*
6. *NAVMAT Manual P3941-A*

NAVAIR 5335

NAVAL AIR SYSTEMS COMMAND

ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 5



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NAVAIR EMC MANUAL

CHAPTER 5
COMPATIBILITY ENGINEERING

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THE EMC PROBLEM

The rapid growth of problems associated with electromagnetic radiation brings belated recognition of the need for electromagnetic compatibility engineering. The problem is not a new one. It is as old as the art of radio communication itself. The original radio transmitters generated Hertzian waves by means of a spark gap, and the wavelength of the resultant emission was determined largely by the antenna structure itself. The term wavelength was not a precise description; it represented the center point of an extremely broad band of emission. Because each station occupied a large segment of the spectrum, two stations in the same geographic area could not operate simultaneously. In other words, compatibility became a problem as soon as a second station came on the air.

As late as 1928, and despite the proved superiority of CW (also an inexact term), spark transmitters continued in operation because users claimed lack of technical and financial ability to conform to the tighter technical specifications. Spark transmitters were finally shut down (except for emergency use at sea) when increasing pressure for the accommodation of more stations and services brought about regulations for spectrum conservation. But old ideas die hard the four-piper destroyers that the Navy returned to service just before entry into World War II were recommissioned with a spark transmitter as their emergency radio equipment. Furthermore, the theoretical principles of single sideband (SSB) and its spectrum conservation capabilities were known as early as 1922, but only in recent years have designers been able to meet the stringent technical requirements. Multitudes of users have already converted to SSB or Independent Side Band (ISB), and the time is now rapidly approaching when double-sideband-with-carrier for point-to-point communication will go the way of spark.

A major problem facing the U. S. military services is that of ensuring that electronic devices will function satisfactorily when used under operational environmental conditions. The limiting factor is the finite nature of the radio frequency spectrum, wherein communications-electronics requirements of all interests must be accommodated. Factors contributing to the worsening of an already critical problem are increasing complexity of advanced systems, operation of more systems closer together geographically and spectrally, specification requirements for less weight, denser packaging, better heat dissipation, better G-loading and vibration performance, higher-speed digital devices, greater arrays of equipments in vehicles and ground or shipboard sites,

continue through research, development, evaluation, and ultimate tactical deployment. An awareness of EMC requirements must remain in effect throughout the life cycle of each electromagnetic device.
longer periods or greater frequency of operation, and further crowding of the electromagnetic spectrum.

Fundamentally, the EMC problem consists of finding means whereby claimants to spectrum occupancy can share the spectrum in harmony, not only with each other but with a multitude of restricted and incidental radiating devices. There is no single, simple solution to the problem. Consideration of EMC requirements must begin at the concept of a technological capability and

The EMC problem can be factored into two interrelated functions: design compatibility, and operational compatibility. Design compatibility is the technical characteristic built into devices, equipments, or systems whereby electromagnetic interference or susceptibility is held below limits which permit it to function reliably without suffering or causing degradation in the presence of similar or different electromagnetic devices. Operational compatibility involves the application of sound frequency management, effective EMI environment control, and clear concepts, plans, and doctrine leading to reliable exercise of command, communications, and control through the use of electromagnetic devices. Although design compatibility is necessary to operational compatibility, neither can take precedence in terms of importance.

OPERATIONAL COMPATIBILITY

Operational compatibility consists of those factors of operating times, frequencies, modes, procedures, field intensities, and locations that permit an equipment or system to gain access to the electromagnetic spectrum in a manner compatible with other occupants Operational compatibility requirements must be taken into consideration early in the planning stages of procurement projects involving electromagnetic devices in order to provide for frequency assignments in an already-crowded spectrum. Design characteristics of frequency, modulation bandwidth, power output, flexibility of modes and channels, and other technical matters are dictated by the availability of frequency allocations or assignments.

Power output design considerations must take into account the power in frequency sidebands and other spurious emissions as well as that at the center frequency. Therefore it could be an expensive mistake to proceed into the hardware design stage before being assured that the proposed development could be fitted into the current or projected electromagnetic environment. For example, radar concepts, and the doctrines relating to its use, were developed without significant frequency restraints during World War II because there were no spectrum allocations to inhibit them. Before the war ended, the fallacies of such disorganized growth became apparent when the ambient EMI of a naval task force became so great that radar surveillance was self-defeating.

SPECTRUM ENGINEERING

The usable radio frequency spectrum is a great, free, natural resource, available to and used by all nations to satisfy their communications-electronics requirements. It supports a multitude of radio operations in the provision of national and international services, but it is being challenged to do more. It is limited, has other constraints, and does not respect national boundaries. Some operations, such as communications with aircraft and ships that travel to every part of the world, are global in nature.

For international allocation purposes, the radio frequency spectrum can be said to extend from about 10 kHz to 40 GHz. However, the classified Appendix 1 of the OTP's "Manual of Regulations and Procedures for Radio Frequency Management," containing the U. S. Government Table of Frequency Allocation for 1 May 1971, considerably extends this range of spectrum allocation in the United States. For working convenience, the radio frequency spectrum has been divided into a number of bands. The various portions of the spectrum have different characteristics, so that one portion cannot be used interchangeably with another. The spectrum is unique among natural resources in that it cannot be consumed through use, but neither is it sufficient in scope to accommodate all activities that want to use it. Like our natural resources of air and water, it is also subject to pollution. Therefore, careful conservation measures must be employed to fit as many radio services as possible compatibly into the spectrum.

Because no segment of the spectrum is consumed through use, a frequency can be assigned again to another activity sufficiently separated geographically, or it can be shared in terms of time. Knowledge of propagation characteristics of the frequency with respect to the propagation medium is essential to this process. Figure 5-1 shows the geographical division of the international frequency allocations into three regions; some allocations are worldwide, and some are regional. Allocations are further subdivided within each region into allotments for each class of radio service. National subdivisions are made for frequency channel assignments to each particular station or group of stations. For large nations like the U. S., each frequency channel can be assigned more than once when the stations concerned are sufficiently separated geographically or operate at different times. Geographical separation between stations sharing a frequency assignment also requires observation of power ceiling constraints in most cases.

Furthermore, each assignment cannot be for a single frequency; it requires a frequency channel of sufficient bandwidth to accommodate modulation characteristics and stability of frequency control. This means that in addition to geographical or time separation, each assignment calls for a frequency channel wide enough to maintain operational compatibility.

Frequency Spectrum Regulation

The use of radio for communication became practical about 1898. In 1903 the first International Radio Conference was held in Berlin to establish certain operating rules and tariffs. Regulations were established in 1906 for

ship-to-shore service, recognizing 300 meters (1000 kHz) and 600 meters (500 kHz) as the only allocations. The 500 kHz allocation continues even today as the international calling and distress frequency. In 1912, the second International Radio Conference was held in London to establish international regulation for frequency use, and the allocated spectrum was extended to include all frequencies between 150 kHz and 1000 kHz. Everything above 1.5 MHz (200 meters and down) was considered a wasteland beyond the technological barrier and was made available to amateur experimenters. After the amateurs developed the techniques and the devices to demonstrate the value of short waves, most of this portion of the spectrum was quickly taken from them.

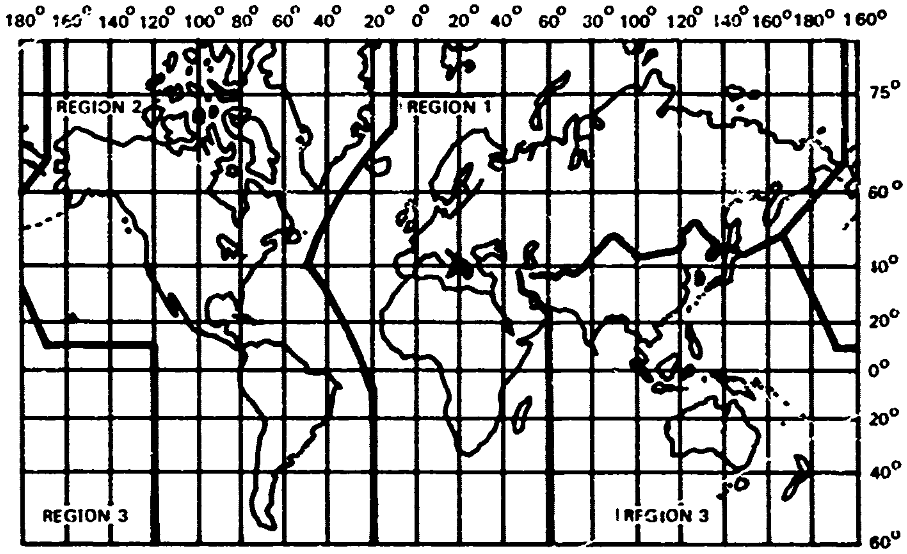


FIGURE 5-1 WORLD FREQUENCY ALLOCATION REGIONS

Because of the rapid growth of frequency spectrum occupancy, the International Radio Conference, Washington 1927, expanded spectrum allocations to cover 10 kHz to 23 MHz. At this time, 23 MHz was considered to be a technological barrier and everything above this frequency was given over to experimenters. At the International Radio Conference, Madrid 1932, the upper technological limit was felt to be 30 MHz; at the International Telecommunication Conference, Cairo 1938, it was 200 MHz; at the International Radio Conference at Atlantic City it was 10.5 GHz; and by the time of the Administrative Radio Conference, Geneva 1969, it had reached 40 GHz. The ITU Extraordinary Administrative Radio Conference for Space, Geneva 1963, recognized the extension of man's sphere of influence into space and made provisions for satellite communication, satellite navigation, and radio astronomy. Experimental allocations in the U. S. were extended as high as 300 GHz. Changes in the aeronautical and maritime/oceanographic usage of

frequencies were made by the ITU Extraordinary Administrative Radio Conference for Preparation of a Revised Allotment Plan for the Aeronautical Mobile Service, Geneva, first session 1964, second session 1966, and the ITU World Administrative Radio Conference for the Maritime Mobile Service, Geneva, first session 1964, second session 1966, and the ITU World Administrative Radio Conference for the Maritime Mobile Service, Geneva 1967. The latest ITU conference was the World Administrative Radio Conference for Space Telecommunications in Geneva in July 1971.

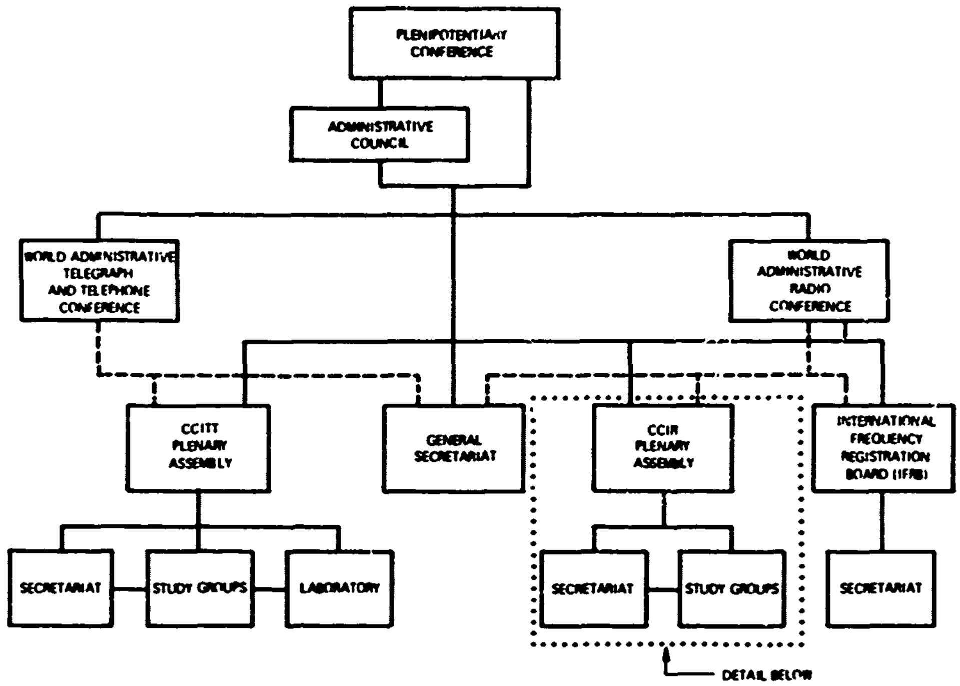
Within the United States, the Federal Radio Commission (FRC) was created in 1927 to regulate allocations and types of emission in an effort to resolve conditions that were becoming chaotic. In 1934, the U. S. Congress passed the basic Communications Act which, with its amendments, remains the fundamental legislation governing radio and wire communications service in the U. S. The act created the Federal Communications Commission (FCC) with greater regulatory powers, superseding the older and nearly impotent FRC.

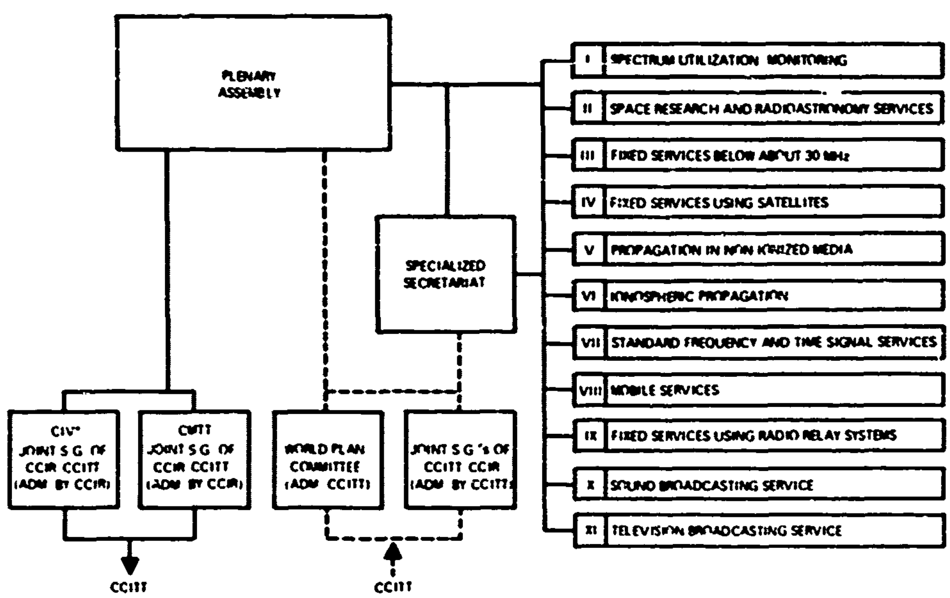
National allotments and assignments in technologically advanced countries nearly always lead international allocation provision. It is difficult, in advance of proof of need for a new radio service or proof that a new technique will be successful, to persuade most of the ITU member countries to agree to changes that may require them to adjust existing operations at considerable expense, particularly when they are not in a position to play a significant role in connection with the new technique. Therefore, pending such proof, it is frequently necessary to develop new techniques such as space communication, radio astronomy, or oceanography within the general provision that any frequency may be used other than as provided in the ITU Table of Frequency Allocations only on the express condition that harmful interference shall not be caused to services operating in accord with the ITU Convention and Radio Regulations.

Because use of the radio spectrum has grown in advance of adequate knowledge of the behavior of the various bands of radio frequencies, a worldwide situation has developed in which allocations are not always ideal from a technical standpoint. Unfortunately, the cost of drastic changes in the allocations as well as the social and economic effects of such changes presents problems of major magnitude. Many national and international agencies are engaged in study and management of radio spectrum allocations for optimum usage.

International Telecommunication Union (ITU)

Of necessity, the nations of the world must work together from a common base of some sort to avoid total chaos in telecommunications. This base is the International Telecommunication Convention with its appended Radio Regulations, evolved and produced by the International Telecommunications Union (ITU) through a long series of international conferences. To facilitate efficiency and understanding in worldwide use of telecommunications, the ITU, established in 1865 as the International Telegraph Union to regulate





*S.G. XIV CONTINUES ON INTERIM BASIS PENDING APPROVAL OF THE JOINT GROUP BY THE CCITT AT ITS NEXT PLENARY ASSEMBLY

FIGURE 5-2 INTERNATIONAL TELECOMMUNICATION UNION ORGANIZATION

international wire services, now exists to: (a) maintain and extend international cooperation for improvement and rational use of telecommunication of all kinds, (b) promote development of technical facilities and their most efficient operation to improve telecommunication services, and (c) harmonize the actions of nations in attainment of these common ends. Figure 5-2 illustrates the organization of the ITU.

When the ITU became a specialized agency of the United Nations in 1947, its membership included 78 nations and it recognized 15 different radio services in an allocated spectrum extending to 10.5 GHz. By 1969, membership had grown to 137 nations, 26 radio services were recognized, and the spectrum had been allocated to 40 GHz. Among its functions, the ITU: (a) effects the allocation of the radio frequency spectrum and registration of radio frequency assignments in order to avoid harmful interference between radio services of different countries; (b) coordinates efforts of other activities to eliminate harmful interference and improve the use made of the radio spectrum; (c) promotes the adoption of measures for ensuring the safety of life through the cooperation of telecommunication services; and (d) undertakes studies, makes regulations, adopts resolutions, formulates recommendations and opinions, and collects and publishes information concerning telecommunication matters for the benefit of all members and associate members.

The Plenipotentiary Conference of the ITU, which normally meets every five years, is composed of delegations representing member nations and associate members. Such conferences determine the general policies of the ITU, review reports, and revise the International Telecommunication Convention as considered necessary. The Plenipotentiary Conference also concludes or revises, as necessary, agreements between ITU and other international organizations.

The Administrative Council, consisting of 29 members of the ITU chosen to represent all parts of the world, meets annually and acts for the Plenipotentiary Conference between sessions of that body.

Administrative Conferences may be either world administrative or regional administrative conferences. Such conferences are usually convened to consider specific telecommunication matters. The agenda of a world administrative conference may include revision of Administrative Regulations as well as other questions of world character within the competence of the conference. The international Radio Regulations stem from decisions of World Administrative Radio Conferences.

Administrative Radio Conferences also designate a number of special purpose frequencies, often with guard bands. For safety of life at sea, 500 kHz is assigned for telegraphy, 2182 kHz for telephony, 8364 kHz for high frequency telegraphy, and 156.8 MHz for VHF telephony. Comparable safety frequencies in aviation are 121.5 and 243 MHz. Standard frequencies are also designated for stations such as WWV and CHU. Natural phenomena also enter the allocations at spectral lines of concern to radio astronomers, based on the resonant frequency of elements of astronomical interest.

The International Frequency Registration Board (IFRB) was created by the ITU International Radio Conference. Washington, in 1947. It ensures formal

international recognition and the orderly recording of frequency assignments by the different countries, by establishing in accord with the procedures stated in ITU Radio Regulations, the date, purpose, and technical characteristics of each assignment.

The date of registration with the IFRB for any assignment determines its relative priority if interference occurs. IFRB furnishes advice to members and associate members to assure operation of the maximum practical number of radio channels in those parts of the spectrum where harmful interference may occur. The Board performs additional duties concerned with the assignment and use of the frequencies prescribed by a conference of the ITU or by the Administrative Council with the consent of the majority of the members. Maintenance of essential records is an inherent part of IFRB duties.

At ITU Radio Conferences, member nations submit their proposals for frequency allocations to the Secretary General of the ITU, preferably four to six months before the conference. Meetings are then held to discuss the technical implications of such allocations and to resolve conflicts in requirements for frequencies. Generally, proposals for changes in frequency allocations are circulated for review by all members of the conference. Occasionally, proposals are also made from the floor. Final recommendations are made to the plenary body for formal vote after negotiation in the working groups.

Although the radio conferences allocate various bands of frequencies for different types of services, they do not assign frequencies to particular users. Licensing or authorizing transmissions by individual users is the responsibility of each member nation in accord with the Tables of Frequency Allocation that represent international agreement on frequencies within the ITU. When agreement is reached on any matter at an ITU radio conference, the decision is embodied in ITU radio regulations. These radio regulations are then submitted to the ITU member nations for ratification as a multilateral treaty.

U. S. Department of State

The Secretary of State is responsible for determining the United States' position, which will be projected internationally, and to ensure the proper conduct of international coordination and negotiations to advance such positions. The Director of Telecommunications Policy (DTP) and the Federal Communications Commission (FCC) have the responsibility to establish national telecommunication policies and formulate national positions for international projection, and to assist and give policy advice to the Department of State in the field of international telecommunication policies, positions, and negotiations. All United States proposals to and coordination with the ITU, other related bodies and organizations, and other administrations, are made or carried out through the Department of State.

In preparing for a Plenipotentiary Conference, the Department of State takes the initiative and forms a Main Preparatory Committee composed of representatives of interested Government and non-Government organizations. Subcommittees are formed to study and make recommendations regarding

particular problems or parts of the convention. These recommendations are considered in the development of U. S. proposals by the Main Committee and recommended to the Department of State for submission to the Secretary-General of the ITU some six to eight months in advance of the conference. The ITU Secretariat translates all proposals into the several working languages of the ITU, reproduces them, and sends complete sets of the proposals to each member nation. Upon receipt of the compendium of proposals, the U. S. Main Committee considers all proposals, develops currently-recommended U. S. positions on each item, and advises the Department of State regarding instructions to the U. S. delegation.

Preparing for Administrative Radio Conferences is more complex and time-consuming. Administrative Radio conferences may discuss only items included in their agenda which is determined by the ITU Administrative Council with the concurrence of a majority of the members involved. It includes all questions directed by a Plenipotentiary Conference. Usually the Interdepartmental Radio Advisory Committee (IRAC) and FCC develop proposed agenda items and the U. S. position concerning them, for parallel recommendation by the DTP and the FCC to the Department of State, and ultimately for use by the U. S. representative to the ITU Administrative Council

Upon receipt from the Department of State of an approved agenda for a forthcoming ITU Administrative Radio Conference, IRAC and FCC normally develop, through a set of joint meetings, U. S. proposals, positions, and instructions to the U. S. delegation for parallel recommendation by the DTP and FCC to the Department of State for use in connection with each agenda item.

As a final step in preparing for the conference, the Department of State designates the U. S. delegation, which meets to put the U. S. proposals into final form and to recommend to the Department of State any additional instructions they need. The Department of State may convene a Government-Industry Group to assist in final preparation or to explain the U. S. proposals.

On completion of an Administrative Conference, IRAC/FCC indicates the actions needed to implement the U. S. international obligations undertaken at the conference. At the same time, the Department of State prepares the documents necessary for the President to get the advice and consent of the Senate to his ratification of conference results. Upon receipt of such advice and consent, the President ratifies the conference results, and the Department of State sends the ratification to the Secretary-General of the ITU. When convenient, the Secretary of State proclaims that the President has ratified the conference results and that they have the force of law. Action is completed by the FCC's effecting changes to its rules and regulations, and the DTP's revising its Manual of Regulations and Procedures for Radio Frequency Management.

National Objectives for Use of The Spectrum

A basic tool for United States use of the spectrum is the National Table of Frequency Allocations, which is composed of the DTP (Government users) and FCC (non-Government user) tables. The National Table of Frequency

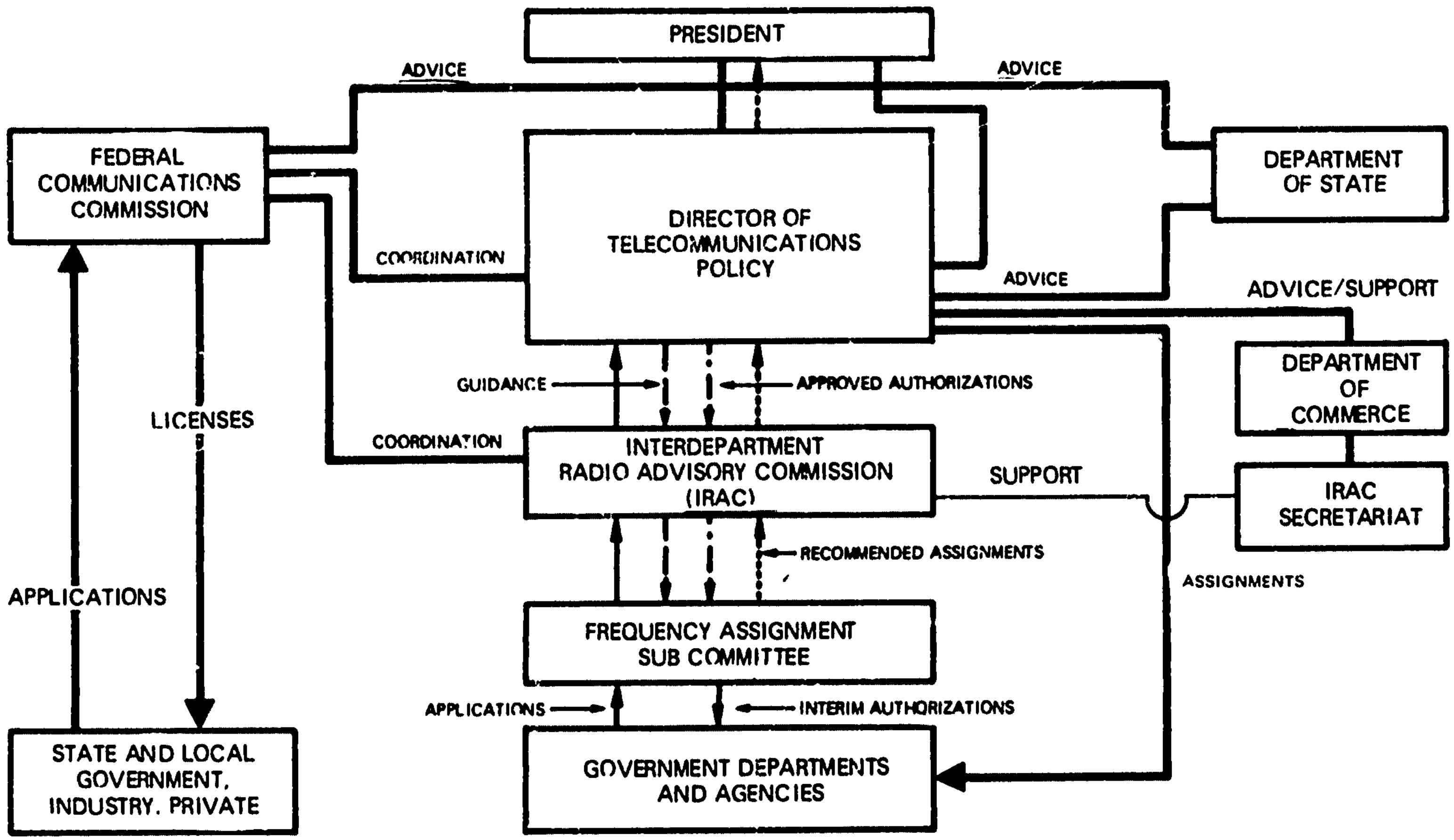


FIGURE 5-3 NATIONAL FREQUENCY COORDINATION AND ASSIGNMENT

Allocations is a dynamic instrument under continuing review, and changed by DTP/FCC agreement as needed to meet changing requirements.

Formulation of national objectives for the use of the radio spectrum and of policies to ensure operational compatibility of all national objectives, is clearly an essential role of the Federal Government. Goals are established and policies are made by the Congress, by the courts, by the President, and by the DTP for Government use, and by the FCC for public use. Policy is made through treaties to which the United States adheres, through executive agreements, by executive departments and agencies in the discharge of their telecommunication responsibilities, and by custom and precedent. A statement of policies designed to achieve electromagnetic compatibility is required for the guidance of responsible officials and the public, if the nation is to make maximum use of the radio spectrum.

The President, as Chief Executive and Commander-in-Chief of the Armed Forces of the United States, has broad responsibility for U. S. use of telecommunication resources to meet the changing needs of national security, defense, and warfare. The President uses several Government agencies to assist him in the discharge of his telecommunication responsibilities.

Figure 5-3 illustrates Government management of the frequency at the national level. The frequency spectrum is a natural resource under sovereign domain, and in time of emergency the President may authorize any use of any portion of the spectrum as he may deem fitting, as may the head of any other government within his own area of control.

Director of Telecommunications Policy

Recognizing the need for prudent administration of the use of the radio spectrum, the President, by Executive Order 11556, September 9, 1970, provided for a Director of Telecommunications Policy to act for him or under his authority and control in the discharge of his telecommunication responsibilities under the Communications Act and the Communications Satellite Act, and, in a war emergency, certain of his wartime powers over national telecommunications; and to be the President's principal advisor on telecommunications. The structure and interests of the Office of the Director of Telecommunications Policy are shown in Figure 5-4. Subject to the authority and control of the President, the Director of the Office of Telecommunications Policy shall:

(a) Serve as the President's principal adviser on telecommunications.

(b) Develop and set forth plans, policies, and programs with respect to telecommunications that will promote the public interest, support national security, sustain and contribute to the full development of the economy and world trade, strengthen the position and serve the best interests of the United States in negotiations with foreign nations, and promote effective and innovative use of telecommunications technology, resources, and services. Agencies shall consult with the Director to insure that their conduct of telecommunications activities is consistent with the Director's policies and standards.

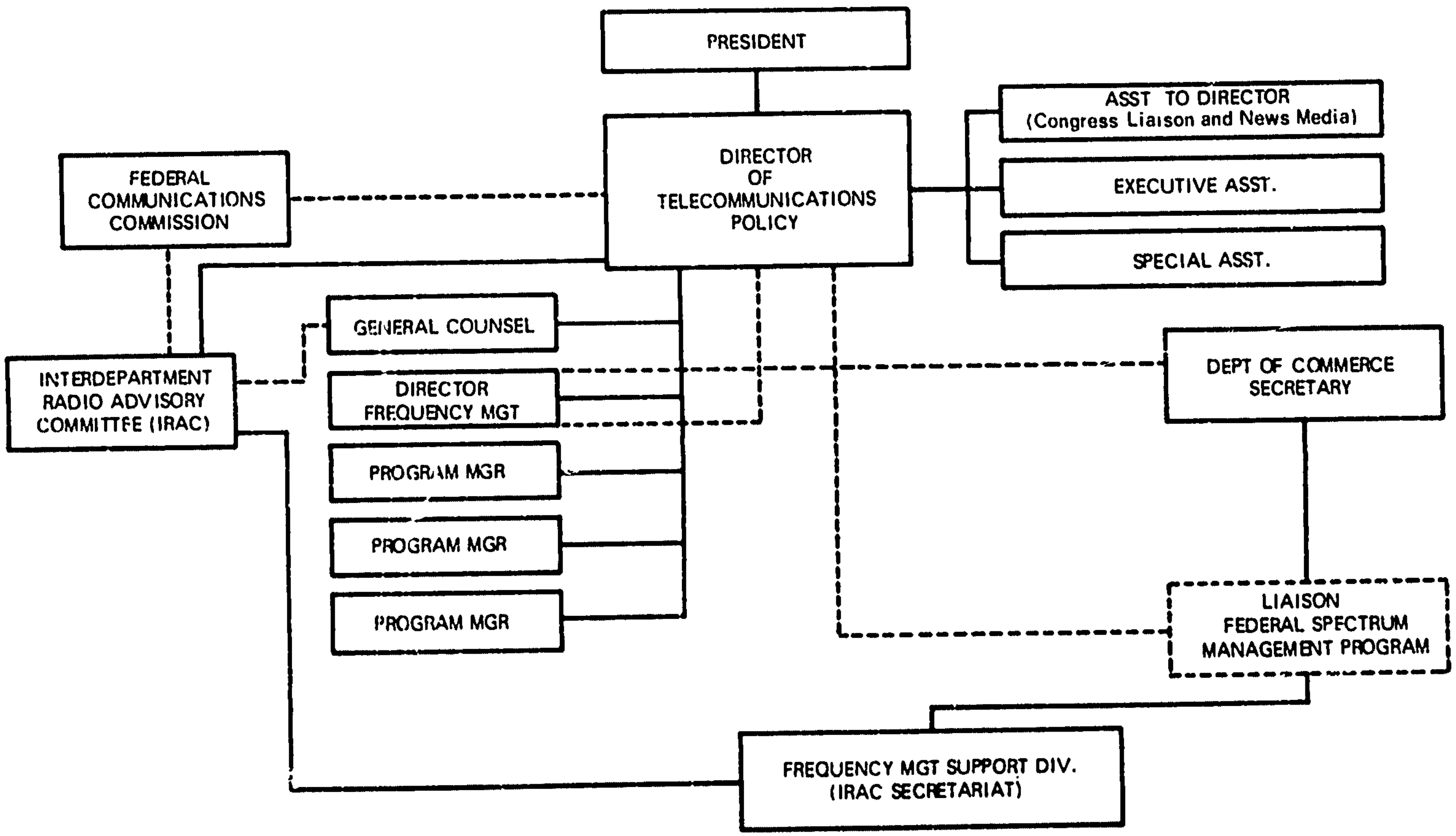


FIGURE 5-4 OFFICE OF THE DIRECTOR OF TELECOMMUNICATIONS POLICY,
EXECUTIVE OFFICE OF THE PRESIDENT

(c) Assure that views of the executive branch are effectively presented to the Congress and the Federal Communications Commission on telecommunications policy matters.

(d) Coordinate those interdepartmental and national activities conducted in preparation for U. S. participation in international telecommunications conferences and negotiations, and provide to the Secretary of State advice and assistance with respect to telecommunications in support of the Secretary's responsibilities for the conduct of foreign affairs.

(e) Coordinate the telecommunications activities of the executive branch and formulate policies and standards therefor, including but not limited to considerations of interoperability, privacy, security, spectrum use, and emergency readiness.

(f) Evaluate by appropriate means including tests, the capability of existing and planned telecommunications systems to meet national security and emergency preparedness requirements, and report the results and any recommended remedial actions to the President and the National Security Council.

(g) Review telecommunications research and development, system improvement and expansion programs, and programs for the testing, operation, and use of telecommunications systems by Federal agencies. Identify competing, overlapping, duplicative or inefficient programs, and make recommendations to appropriate agency officials and to the Director of the Office of Management and Budget concerning the scope and funding of telecommunications programs.

(h) Coordinate the development of policy, plans, programs, and standards for the mobilization and use of the nation's telecommunications resources in any emergency, and be prepared to administer such resources in any emergency under the overall policy direction and planning assumptions of the Director of the Office of Emergency Preparedness.

(i) Develop, in cooperation with the Federal Communications Commission, a comprehensive long-range plan for improved management of all electromagnetic spectrum resources.

(j) Conduct and coordinate economic, technical, and systems analyses of telecommunications policies, activities, and opportunities in support of assigned responsibilities.

(k) Conduct studies and analyses to evaluate the impact of the convergence of computer and communications technologies, and recommend needed actions to the President and to the departments and agencies.

(l) Coordinate Federal assistance to State and local governments in the telecommunications area.

(m) Contract for studies and reports related to any aspect of his responsibilities.

(n) The Director is responsible for assigning frequencies to radio stations belonging to and operated by the United States, or to classes thereof, and for the amendment, modification, or revocation of these assignments including any previous assignments that have been made. The Director is the authorizing agency for construction, frequency assignments, and operations of foreign

governments of radio stations at the seat of government.

(o) As may be permitted by law, the Director shall establish such interagency advisory committees and working groups composed of representatives of interested agencies and consult with such departments and agencies as may be necessary for the most effective performance of his functions. To the extent he deems it necessary to continue the Interdepartment Radio Advisory Committee, that Committee shall serve in an advisory capacity to the Director. As may be permitted by law, the Director also shall establish one or more telecommunications advisory committees composed of experts in the telecommunications area outside the Government.

(p) The Director shall issue such rules and regulations as may be necessary to carry out the duties and responsibilities delegated to or vested in him by this order.

(q) All executive departments and agencies of the Federal Government are authorized and directed to cooperate with the Director and to furnish him such information, support and assistance, not inconsistent with law, as he may require in the performance of his duties.

The Frequency Management Director functions with respect to radio frequency management and related matters within the Executive Branch of the Government. Specifically, the Director is responsible to the DTP, working with the FCC and with and through IRAC as appropriate, to:

(a) direct planning for United States use of the radio spectrum;

(b) direct frequency management within the Executive Branch so that Government use of the spectrum is effective, efficient, and sound;

(c) discharge Presidential functions arising from Section 305 of the Communications Act of 1934 and assigned to the DTP;

(d) assist and formulate policy advice to the Department of State in the discharge of its functions in the field of international telecommunication policies, positions and negotiations;

(e) review IRAC frequency assignments and recommendations, approve those found to be satisfactory, and adjudicate matters referred for consideration;

(f) assist and advise the DTP as otherwise necessary or directed; and

(g) chair the IRAC.

Interdepartment Radio Advisory Committee

The Interdepartment Radio Advisory Committee (IRAC) was organized in 1922 upon invitation of the Honorable Herbert C. Hoover, then Secretary of Commerce, who administered the Radio Act of 1912. Secretary Hoover Acted in response to a suggestion by the Chairman of the First National Radio Conference, Washington, D. C., that interested Government departments designate representatives to a committee to find the most effective use of the wavelengths then being used for Government broadcasting. IRAC soon broadened its objectives to include all radio matters of interdepartmental interest. The President, in a letter to the Secretary of Commerce in 1927, affirmed the action of IRAC in assuming the responsibility of advising the

President with respect to frequency assignments for the Government. By successive Executive Orders, IRAC was directed to report to and assist the evolving executive offices on emergency planning, and finally to report to the Director of Telecommunications Policy.

The mission of IRAC is to formulate and recommend to the DTP objectives, plans, and actions as appropriate in connection with the management and usage of the radio spectrum in the national interest by the departments and agencies of the U. S. Government.

IRAC is now composed of representatives of the Department of State, Treasury, Defense (Army, Air Force, Navy), HEW, Interior, Justice, Agriculture, Commerce, Transportation (Coast Guard and FAA), and NASA, the Atomic Energy Commission, the U. S. Information Agency, and the General Services Administration. The FCC is not a member of IRAC; however, the FCC has a liaison representative who works with IRAC and its subcommittees. The IRAC permanent sub-structure consists of the Frequency Assignment Subcommittee (FAS), the Spectrum Planning Subcommittee (SPS), the International Notification Group (ING), and two special groups; the Aeronautical Assignment Group (AAG) and the Military Assignment Group (MAG).

IRAC is authorized, subject to DTP approval, to assign frequencies to Government radio stations on an interim basis, and to withdraw or modify such assignments in the interest of compatibility. Such assignments are later reviewed by DTP and those found to be satisfactory are approved. Frequency assignment matters are also referred to the DTP through the Frequency Management Directorate when directed to do so, when policy guidance is needed, when agreement cannot be reached within the IRAC/FCC, or when requested by any agency. Matters of considerable importance, such as significant changes to the Table of Frequency Allocations, Government use of a frequency band that must be considered by the FCC, or advice to the Department of State, are recommended to the DTP for policy coordination and approval.

Department of Commerce

In accordance with the provisions of Executive Order 11556 of 9 September 1970, the Secretary of Commerce shall support the Director in the performance of his functions, shall be a primary source of technical research and analysis and, operating under the policy guidance and direction of the Director, shall:

(a) Perform analysis, engineering, and administrative functions, including the maintenance of necessary files and data bases, responsive to the needs of the Director in the performance of his responsibilities for the management of the radio spectrum.

(b) Conduct technical and economic research upon request to provide information and alternatives required by the Director.

(c) Conduct research and analysis on radio propagation, radio systems characteristics, and operating techniques affecting the use of the radio spectrum in coordination with specialized, related research and analysis performed by

other Federal agencies in their areas of responsibility.

(d) Conduct research and analysis in the general field of telecommunication sciences in support of other Government agencies as required and in response to specific requests from the Director.

(e) Conduct such other activities as may be required by the Director to support him in the performance of his functions.

Department of Defense

The Department of Defense (DoD), in addition to its defense role, has significant responsibilities in telecommunications. The Presidential Memorandum of August 21, 1963, established the National Communications System (NCS) to provide necessary communication for the Federal Government under all conditions ranging from a normal situation to national emergencies and international crises, including nuclear attack. The NCS was to be established and developed by linking together, and by continuously improving and extending, the communication facilities and components of the various Federal agencies. The Secretary of Defense was designated executive agent for the NCS with responsibility to: design, develop operational plans, and provide operational guidance with respect to all elements of the NCS, including requests for assignment of radio frequencies for the NCS and monitoring of their use.

The Secretary of Defense has designated an Assistant Secretary of Defense to, among other things, act as DoD coordinator in command, control, and communication; review progress in the accomplishment of NCS responsibilities; and recommend to the Executive Agent for the NCS, as appropriate, measures for improving the NCS and for securing efficiency, effectiveness, and economy. The Secretary has designated as Manager of the NCS, the Director of the Defense Communications Agency, who is also Chairman, Military Communications-Electronics Board (MCEB). The Assistant Secretary of Defense (Telecommunications) is also the principal staff assistant to the Secretary of Defense in functional telecommunication.

The Department of Defense is an integral component of the U. S. National Frequency Management structure. Radio frequency matters may involve the Offices of the Secretary of Defense, Defense Research and Engineering, Assistant Secretary of Defense (Installation and Logistics), Assistant Secretary of Defense International Security Affairs, and Assistant Secretary of Defense (Management), as well as the three military departments.

The prime focal points, however, are the principals of the communications-electronics staffs of the military departments who respond through the Joint Staff or intra-departmental chain according to the nature of the matter under consideration. The flow of authority on frequency matters may be multilateral: through the Interdepartment Radio Advisory Committee in common with all Government agencies, or through purely military channels through the Secretary of Defense. Coordination on a single Navy frequency problem may go through both chains. Policy and assignment of responsibilities

within the Department of Defense are established by DoD Directive 4650.1 (Management and Use of the Radio Frequency Spectrum).

Military Communications-Electronics Board

Originally established as the Joint U. S. Communications Board (JCB), the Military Communications-Electronics Board (MCEB) was chartered in its present form by the Secretary of Defense in 1958. The mission of the MCEB as set forth in DoD Directive 5100.35 of 29 December 1962 is to:

(a) Coordinate military communications-electronics matters among DoD components, between DoD and other governmental departments and agencies, and between DoD and representatives of foreign nations.

(b) Provide DoD guidance and direction in functional areas of military communications-electronics for which the MCEB is responsible.

(c) Advise and assist, as requested, concerning military communications-electronics matters, the Secretary of Defense, the Joint Chiefs of Staff, the military departments, and other DoD components.

Under its charter, the MCEB is authorized to establish panels to assist in its mission and has the right to delegate certain authority to the panels, including assignment of frequencies. Joint panels now established under MCEB are:

Electronic Warfare	Security and Cryptographic
Joint Frequency Panel	Communications Publications
Aids to Navigation	Call Signs
C-E Plans and Policies	Equipment and Standardization
Warning and Target Information	Methods and Procedures

Joint Frequency Panel

The Joint Frequency Panel (JFP) is responsible to the MCEB in the areas of radio propagation and frequency allocation, coordination, and assignment. The JFP consists of at least one member and an alternate from each service or agency within the MCEB who has an interest in the activities of the panel, plus one representative and an alternate from the Coast Guard. Present membership consists of Army, Navy, Air Force, Joint Staff (J-6), USMC, Coast Guard, DCA and NSA.

The JFP is responsible to the MCEB for implementation of the Operational (Frequency Management) Area of the DoD EMC Program, including coordination of individual service efforts to implement the operational aspects of the Program. Its responsibilities include continuously evaluating the operational aspects of the Program and giving advice to the Director, C-E, Joint Staff, and the Director of Defense Research and Engineering (DDR&E) through the MCEB, with respect to policy and other pertinent matters.

The JFP is also responsible to the MCEB for advising the Director, C-E, Joint Staff, through the MCEB, concerning the establishment of priorities among projects referred to ECAC. These duties include defining the nature of spectrum signature and environmental data and preparing and implementating plans for collecting such data.

The JFP makes recommendations to the MCEB regarding frequency matters, including policy coming under Joint Staff cognizance, and implements those JFP decisions on frequency matters that involve no change in JCS policy. The JFP coordinates radio frequency allocations to meet new military requirements, and exchanges frequency allocation information among the military services. The JFP maintains liaison with appropriate Government agencies on all frequency matters concerning them, except those of an individual service nature. Normally, unless a change in JCS policy is involved, such liaison may be effected by the separate services acting together or individually. The JFP coordinates the separate views of the military services on frequency matters before presentation to other Government and non-Government agencies, coordinates and assigns frequencies to meet military requirements other than those concerning an individual service, and arranges for changes in allocations and assignments of frequencies within those available to the military.

The JFP recommends action to MCEB for collection, analysis, evaluation, dissemination, and use of radio wave propagation information, and coordinates research and development and operational requirements for radio wave propagation information.

The JFP is assisted by the Message Expediting Group (MEG), which is composed of one representative from each of the frequency offices of the Army, Navy, Air Force, and DCA. The individual Department Frequency Management Offices forward incoming messages to the Frequency Assignment Panel (FAP) for timely action. The preparation, substance, and releasing of such replies is the responsibility of the department with primary interest. If MEG is unable to reach agreement on a response by FAP after considering the problem for two consecutive meetings, each member will report the problem to his JFP principal. The JFP Chairman will then initiate action at the JFP level to resolve the matter.

The Military Departments

Skeleton command relationships of the Frequency Management Staff organizations of the three military departments are shown in Figure 5-5. The three directors, who are also principals on the MCEB, are: the Chief of Communications-Electronics, U. S. Army; the Director of Naval Communications, U. S. Navy; and the Director of Command, Control and Communications, USAF. Each performs the duties of frequency management within his department and has MCEB membership responsibilities. He also respects the rights, needs, and authority of others. Each department conducts independent research and development, communications planning, and policy

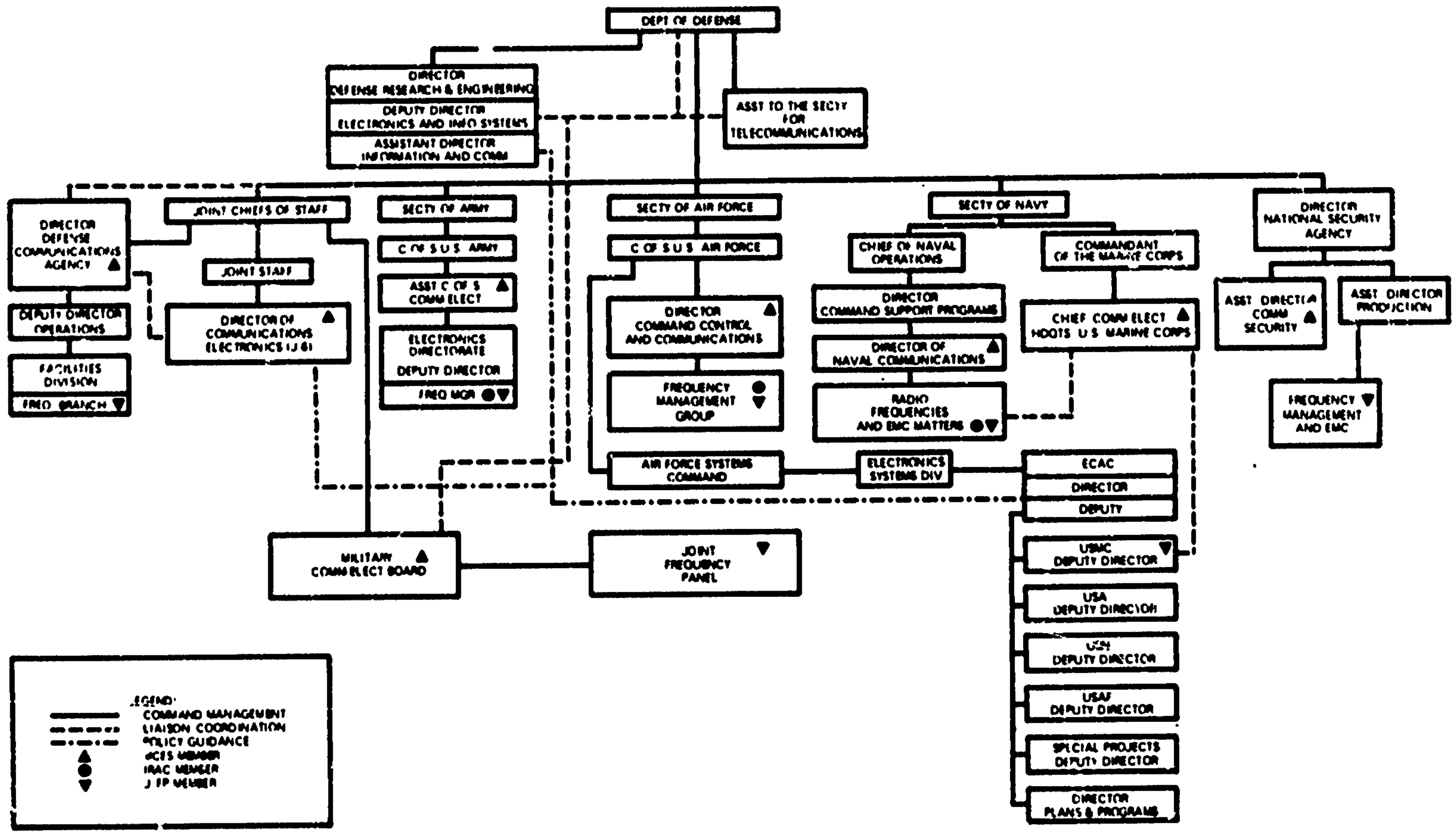


FIGURE 5-5 MILITARY RADIO FREQUENCY MANAGEMENT ORGANIZATION

formulation. Regardless of the fact that the first duty of the Navy Radio Frequency Spectrum Division is to Navy needs, the joint military aspect has a direct bearing upon frequency management organization and procedures, and must be taken into account.

Unified and Specified Commands

These commands, under the Joint Chiefs of Staff, have overall management and control responsibility of all U. S. military use of radio frequencies within their zones of operation. Each unified commander has a Communication-Electronics Directorate to assist him in his field.

Defense Communication Agency

The mission of the Defense Communication Agency (DCA) is to ensure that the Defense Communication System would be so established, improved, and operated as to meet the long-haul point-to-point requirements of the Department of Defense. It is solely a management agency.

Area Frequency Coordinators

Because of critical spectrum usage problems, the MCEB established the DoD Area Frequency Coordination (AFC) System in April 1957. The DoD AFC system has been discussed in Chapter 2. However, current policy guidance is contained in MCEB memorandums MCEB-M 282-67 of 7 July 1967, MCEB-M 572-69 of 2 December 1969, and MCEB-M 166-71 of 27 April 1971. Within the Navy this policy guidance is implemented by OPNAV Instruction 5400.29.

U. S. Navy Frequency Management Procedures

Navy radio circuit controllers carry out a form of frequency management in that they manipulate and select operating frequencies from a list of those available. Compiling a frequency operating plan for a task group, while giving due consideration to potential interference, is frequency management on the part of the flag communicator. Another echelon level involves the person who authenticates or validates new frequency requirements for circuits or channels of fleet commanders. The senior operational frequency management level for the Navy is the Director of Communications, who also serves Joint Staff support functions as a member of MCEB. The MCEB is effectively the senior echelon level in support of a unified commander's communication-electronics organization.

Security precautions and classification of material in frequency management, as in other Navy matters, must be effected in accord with the Navy Security Manual for Classified Matter (OPNAVINST 5510.1) and other directives. Particular awareness of security considerations is required for Navy frequency managers due to the constant flow of official correspondence and

coordination with bodies outside the U. S. Department of Defense, including those of foreign countries.

The Director of Communications has the responsibility for the Department of the Navy to secure joint approval of frequency allocation provisions for all Navy electronic equipment or systems designed to emit or receive electromagnetic energy. Such provision is effected before development, procurement, or adoption of such equipments or systems. Furthermore, CNO does not respond to an originating Navy command or other development activity request for allocation without having first secured joint approval, whether it is for an experimental, developmental, or operational frequency allocation. The importance of allocation in the sequence of furnishing systems to the Fleet is supported by the policy of the Chief of Naval Material (CHNAVMAT), which serves as a checkpoint in preventing expenditures for electronic equipments that lack radio frequency allocation.

To be better prepared for consideration of spectrum allocation policy and engineering matters, the Radio Frequency Allocation Division of the office of Director of Communications, reviews Operational Requirement papers, Specific Operational Requirements, and Technical Development Plans generated within the Navy, advising planning and material offices of any adverse elements and making appropriate recommendations. Difficult or controversial items are studied and resolved by the Frequency Allocation Advisory Board (FAAB), the principal frequency coordinating body within the Navy.

Each DoD component is responsible for processing radio frequency allocation information to the Joint Frequency Panel, and for enforcement of resulting decisions. The procedure is promulgated within the Navy by OPNAVINST 2410.11(series). When R&D efforts are conducted under contract by private industry, it is the responsibility of the cognizant Navy SYSCOM to maintain sufficiently detailed surveillance of such activities to ensure that applications are submitted for experimental or developmental equipments as well as for production equipment for operational use.

Radio frequency allocation, an element of spectrum management, is a control mechanism for using and protecting portions of the radio frequency spectrum in which selected functions are performed. Radio frequency allocation procedures assure professional review and approval of requests to use the spectrum before equipment acquisition, and also assure compliance with Federal regulations, laws, and international agreements. Allocation is spectrum management authority necessary to the acquisition of equipments that can operate in specified frequency bands. Radio frequency allocation must not be confused with radio frequency assignment, which is spectrum management authority whereby the acquired equipment is allowed to radiate under specified conditions at specified geographical locations. A radio frequency assignment or FCC license cannot be granted for an equipment until an appropriate radio frequency allocation has been obtained.

OPNAVINST 2410.11(series) requires that all Navy and Marine Corps agencies engaged in research, development, and procurement of electronic equipment designed to radiate or receive radio frequency electromagnetic energy

submit applications for an appropriate level of radio frequency allocation to the Chief of Naval Operations (CNO) for approval at each stage in the use life of the equipment.

Allocation Level	Use Life Stage
(a) Experimental	(1) All research and development phases (to use equipment as a research tool not intended for eventual operational use)
	(2) Exploratory or advanced development or contract definition portion of engineering development (to test the feasibility of new techniques or concepts or to test the feasibility of adapting existing techniques to new purposes, both with a view toward eventual operational use)
(b) Developmental	(1) Engineering development after contract definition (to development equipment planned for operational use)
	(2) Operational Systems Development (to modify existing operational equipments)
(c) Operational	(1) Production and service use (to produce and operate equipment that has passed the development phase and is planned for operational use for tactical and training purposes, as for test range instrumentation)

Radio frequency allocation requirements apply to equipments in all research and development, procurement and production phases, for equipment intended strictly for experimental use, and for equipment intended for eventual operational use for tactical and training purposes or for non-tactical purposes such as test range instrumentation and other facility operations. Fuzes that employ electromagnetic radiation are specifically excluded.

The electromagnetic compatibility of an equipment under operational conditions is a primary criterion of CNO for evaluating radio frequency allocation applications. Because the first allocation at the earliest life cycle stage is granted on the assumption that production for operational use will materialize, electromagnetic compatibility must be given serious consideration in the application.

The choice of an operating frequency band for a new equipment will affect the project cost, schedule, and operational effectiveness estimates used in the system acquisition decision trade-offs. Impact will be different for each possible frequency band choice due partly to variation in the difficulty of achieving electromagnetic compatibility with other equipments sharing this frequency band and operational environment. The choice of frequency band must also consider other factors that contribute to this differing impact such as cost, component availability, technical risk, performance, maintainability, reliability, size, and weight.

Applications for radio frequency allocations (DD Form 1494) are submitted through applicable systems command to the office of communications with amplifying instructions. Each command records and reviews the application before its submission to CNO. In the office of CNO, applications are studied in the light of existing joint military electronic equipments, established design objectives, and the probable impact from and upon new equipment under development. The effective editions of JANAP 141 (U. S. Joint Military Radio Frequency Allocation Plan) and the Frequency Allocation List, U. S. Military Electronic Equipment, are pertinent. Appropriate equipments are also considered for their impact on the combined environment by an Australian-Canadian-United Kingdom-United States working group of the Combined Frequency Panel. Director of Communications provides the Naval Material Command with copies of all completed frequency allocation actions, whether approved or disapproved, including conditions and recommendations for modification where indicated.

Even though a radio frequency allocation has been approved for a specific transmitter or a Navy installation, specific authority in the form of an assignment is a prerequisite to use of the RF spectrum. Unified Commanders are responsible for control of radio frequency assignments and use within their zones of operation. The Chief of Naval Operations, acting through subordinate commanders such as Naval District Commandants and Fleet Commanders, is responsible for control of radio frequency use and assignment by Navy commands outside the established areas of responsibilities of Unified Commanders.

When it becomes necessary for a Navy command to set up a radio circuit (other than in connection with Fleet tactical plans) at a specific location or for a purpose not already authorized, or in expansion of the frequency provisions of an already authorized operation, specific authority must be obtained from the Chief of Naval Operations or the Unified Commander, as appropriate. In turn, intra-military, national, and international coordination will be effected as necessary.

The first element of this process is validation of the requirements. Various steps in clearance coordination follow, culminating in the assignment. Frequency management action is concluded with entry into pertinent records. Monitoring of assignments to insure continued need and usage is a never-ending follow-up action.

Other Government Agencies

Many Government organizations, with representatives from equipment manufacturers, advisory activities, and universities, are concerned with electromagnetic compatibility problems. Because it is obviously impossible to isolate DoD radiation or susceptibility from other occupants of the common spectrum, the problems are shared and the solutions are subject to consolidation. A study is now underway to find means for correlating the findings of Government and non-Government activities engaged in EMC investigations. EMC records are being examined to find what data are available for EMC calculations and to provide guidance on common formats. Records in the following agencies are being studied: Commerce Department, FAA, FCC, GSA, HEW, IRAC, NASA, and the Treasury Department. Records kept at the DoD Area Frequency Coordination offices and by various commercial users and manufacturers will also be reviewed.

The Frequency Management Advisory Council (FMAC), composed of widely recognized knowledgeable persons from outside the Government, was established in June 1965 by the DTP to give views of the private sector, fresh appraisals, and practical advice on the Government's programs, policies, procedures, and practices in frequency management. The council has subsequently been reorganized and enlarged to include a wider representation of disciplines from industry to equip the FMAC to provide broad industry advice to the FCC and OTM officials as its primary responsibility, as well as to continue its previous activities. The FMAC will, among other tasks:

(a) Advise the DTP on measures to increase the effectiveness of frequency management throughout the executive branch of the Government

(b) Review the procedures, plans, and problems of the IRAC to identify areas where improvements may be needed

(c) Recommend to the DTP any new or more efficient approaches to strengthen frequency management within the Government.

Federal Communications Commission

FCC interference regulations are designed to protect all U. S. users of the electromagnetic spectrum. FCC regulatory and licensing powers are derived from the Congress of the United States and extend to non-Government users of the spectrum. Although the FCC is not a member of IRAC, it provides liaison representation and offers full cooperation in all matters of mutual interest.

Recent amendment of the Communications Act of 1934 (by addition of Section 302 in July 1968) has applied restrictions to the manufacture and sale as well as to the use of devices capable of causing interference. Before this amendment, FCC authority was limited to injunctions against the use of such devices after they were in operation. Enforcement of this new portion of the act is still incomplete, and many devices manufactured before its enactment remain in use. However, users who have encountered interference problems following the purchase of equipments suffering from incompatibilities, such as plastics

formers and garage door openers, have learned to look to the FCC for equipment approval or acceptance.

The FCC has two classes of authorizations: equipment type approval based upon tests made in FCC laboratories, and equipment type acceptance based upon presentations and test data furnished by manufacturers. Some equipments also require certification by a qualified engineer that the equipment, as installed, meets FCC standards as to levels of undesired conducted and radiated RF energy. Neither authorization nor certification is a license to operate the device.

To make sure that licensed devices are operating on frequency and in accord with regulations, and that unlicensed emitters are not causing interference, the FCC operates 30 district offices and 18 monitoring stations. The stations are equipped with direction finders so that unknown interference sources can be located by triangulation. When FCC measurement of frequency, bandwidth, or other characteristics of a device shows that it is operating in an unauthorized manner, or that an unlicensed device is radiating harmful interference, the offender is located and notified to correct the condition.

In addition to domestic monitoring service, the FCC monitoring stations plus 15 monitoring stations owned by RCA, Mackay and others, participate in the International Monitoring Service. This agency gathers spectrum occupancy data from the 33 U. S. monitoring stations and sends it to the International Frequency Registration Board of the ITU for use in frequency allocation studies.

OPERATIONAL PROCEDURES

The DoD EMC Program provides for continuation of EMC awareness into the operational phase of equipments and systems, as well as the application of EMC principles to concepts, doctrine, and field operations. Military procedures, and the characterisitcs of C-E devices used in their conduct, must consider not only the unintentional interference by friendly forces, but the possibility of deliberate enemy ELINT and ECM activities during wartime. Many operational procedures and equipment design features useful in a benign but noisy environment will also be useful in a hostile environment.

Detecting, Reporting, and Resolving EMC Operational Problems

Each DoD component is responsible for developing and implementing procedures and channels for detecting, reporting, solving, and correcting intra-component operational EMC problems. Development of this capability will require procedures for detecting, and channels for reporting, electromagnetic incompatibilities that degrade combat effectiveness in the field. Such publications as Electronics Installation Bulletin (EIB) and Naval Communications Bulletin (NCB) offer a means of disseminating information on EMC problems and solutions when time permits such treatment. Quick reaction to interference, especially in the presence of enemy activity, must be planned and executed promptly and should include safeguards against error or tactical deception. The first step in the achievement of this capability is the education of

C-E personnel in EMC problem detection and investigation. This should lead to application of measurement and analysis techniques to identify the sources of the problems and determine corrective action. Technical and administrative procedures for rapid implementation of required corrective action must be developed. Cognizant organizations should provide feedback to the standards, design, concepts and doctrine, educational and analytical elements of the DoD EMC Program.

Tactical Environment Compatibility

Very few tactical commanders, or even their C-E staffs, are fully cognizant of the electromagnetic environment created by forces under their command. Communication net frequencies, search guards, and missile engagement zones all too often are arrived at through cut-and-try methods. The electronic environment in which tactical radio nets, search and track radars, and guided missile systems must operate is a complex one, especially when heterogeneous combinations of equipments are involved.

EMC data base and analysis services such as that of ECAC enable prediction of EMC degradation for various tactical missions, both existing and planned. By generating and evaluating a series of mathematical models, it is possible to find optimum configuration of equipments, frequency assignments, and force dispositions. The ECAC tactical data file contains information on various tactical deployments ranging from a single command post to a combined-service amphibious/airborne assualt.

Tactical doctrine and availability of forces dictate the combinations of units and their operational disposition. From this it is possible to determine the discrete nets in the formation, the commitment of equipments to nets or guards, and the assignment of search, track, and firing engagement sectors. This is generally expressed in diagrams that include the function and identity of every net member, and the identity, technical characteristics, and operational modes of the equipment used. Frequency assignments incorporating spectrum restrictions are also determined. The source of radio frequencies must be known so as to provide a frequency register from which frequencies can be selected and assigned to each emitter and receiver in the deployment. The techniques for frequency assignment are also important, especially when new automated techniques are being considered.

ADVANCED CONCEPTS AND TECHNOLOGY

Technologically advanced devices and systems, and the way in which they are used, are dependent upon their being able to operate compatibly with other and perhaps older systems.

Orbital NAV/COM Systems

The potential demands for space and satellite communications warrant

serious concern for ways to accommodate them in the frequency spectrum. Before the advent of satellite relays, only that portion of the spectrum below about 25 MHz was useful for intercontinental communication. Much of the spectrum required for satellite communication must be obtained by sharing with already-crowded ground microwave relay services. Technical standards for this sharing are complex and controversial, with each service striving for margin to provide for future expansion. Surface microwave services are already congested, geographically and spectrally, around major metropolitan centers such as New York and Los Angeles where routings must follow devious patterns to avoid interference. Satellite systems offer possibilities for long-haul communications using microwaves, thereby relieving some of the pressure on the HF portions of the spectrum.

The Initial Defense Communications Satellite Project (IDCSP) is regarded as developmental, but it is increasingly used by DoD to pass high priority operational traffic to fixed points. An advanced DoD Tactical Satellite (TACSAT) Program anticipates the feasibility of satellite relays to meet tactical communication needs of the military services even where high mobility is required–in field deployments, and with ships and aircraft. The first orbital relay platform was put into synchronous orbit in February 1969, and has been in operation since then supporting initial development, test, and evaluation of tactical surface hardware and such special operations as the Apollo 10 and Apollo 11 launches. The objectives of this program are to develop operational concepts for satellite communications, to demonstrate and test these concepts, and to evaluate them for future operational systems. Two bands are used, with cross-band switching capability. The SHF band is in the 7-8 GHz range allocated for communication satellite relay by the ITU Extraordinary Radio Conference, Geneva 1963, and consequently it can expect some degree of protection except from other communication satellite relay activities. The UHF band being used by TACSAT is shared with other services, and operational compatibility problems are likely to develop.

The VELA Satellite Program is designed to provide a satellite-based nuclear detection capability from the earth's surface to the outer reaches of space. A Navy Navigation Satellite System, operational since 1964, has led to installation of receivers aboard attack aircraft carriers operating in Southeast Asia. Various studies are underway concerning future uses of such systems; long-term ephemeral predictions for shipboard use are being prepared; and receivers for differential positioning in aircraft and smaller ships are being developed.

Radar and Digital Data Systems

Radars of high resolution and high average power are within the realm of design capability, if the added bandwidth can be tolerated. Over-the-horizon radars are already in use, in frequency bands lower than those expected of radar, but their geographic deployment is limited by local tolerance of their interference potential.

High-speed information-processing networks may be one of the most

important examples of potential uses of the spectrum. The electronic computer is becoming a major ingredient of all our communication and information systems. Rapid developments during the past two decades have yielded a computing technology with capabilities that would have staggered the imagination only 20 years ago. The Navy Tactical Data System (NTDS) is a combination of radar data inputs, computer processing, radio data links, and tactical display that places a high demand on system compatibility.

Bandwidth Considerations

If the most efficient system design is assumed for a fixed data rate for the class of emission, the power required to jam the circuit varies in direct proportion to system bandwidth. The broader the information bandwidth the more difficult it becomes to jam the circuit. Recently there has been considerable development and increasing operational application of new systems of modulation such as wideband frequency modulation and pulse code modulation. These are interesting in that it is possible to exchange bandwidth for signal-to-noise ratio. This means that if more bandwidth is used, the same information can be transmitted in the same time with less signal power, or that circuit reliability will be degraded less in the presence of interference or jamming. Rejection of interference may be increased by the use of wider bandwidth, and the increased rejection allows closer geographical spacing of services. New spread spectrum systems are effective in that they contribute reduced detectable interference per unit bandwidth, and with proper coding and sufficient bandwidth they can work well in strong interference. Conservation of bandwidth is not the sole approach to optimum use of the spectrum. In some cases, it is just as meaningful to restrain power even though extra bandwidth is required.

Current research is being applied to the problems of maximizing the capacity of a system for limited signal power without critical constraints on bandwidth. The power limitations of space probes, surveillance radars, and scatter communication links have emphasized this need. Emphasis on bandwidth compression alone, by frequency management authorities and CCIR, largely reflects traditional assignment patterns.

For a given class of emission, necessary bandwidth is the minimum bandwidth sufficient to ensure the transmission of information at the rate and with the quality required for the system employed, under specified conditions. Emissions useful for the funtioning of the receiving equipment, as, for example, the emission corresponding to the carrier of reduced carrier systems, are included in the necessary bandwidth. Necessary bandwidth may be determined by one of the following methods:

(a) Use of the formulas included in Tables 5-1 and 5-2, which also give examples of necessary bandwidths and designate corresponding emission

(b) Computation in accord with recommendations of the International Radio Consultative Committee (CCIR)

(c) Measurement, in cases not covered by method 1 or 2

Table 5-1. Emission Bandwidth, Amplitude Modulation

Description and class of emission	Necessary bandwidth in cycles per second	Examples	
		Details	Designation of emission
Continuous wave telegraphy, A1.	$B_n = BK$ $K = 5$ for fading circuits. $K = 3$ for nonfading circuits.	Morse code at 25 words per minute, $B = 20$, $K = 5$ Bandwidth: 100 c/s. Four-channel time-division multiplex, 7-unit code, 42.5 bauds per channel, $B = 170$, $K = 5$. Bandwidth: 850 c/s.	0.1A1 0.85A1
Telegraphy modulated by an audio frequency, A2.	$B_n = BK + 2M$ $K = 5$ for fading circuits $K = 3$ for nonfading circuits.	Morse code at 25 words per minute, $B = 20$, $M = 1{,}000$, $K = 5$. Bandwidth: 2,100 c/s.	2.1A2
Telephony, A3	$B_n = M$ for single sideband $B_n = 2M$ for double sideband	Double sideband telephony $M = 3{,}000$ Bandwidth: 6,000 c/s. Single sideband telephony reduced carrier, $M = 3{,}000$. Bandwidth 3,000 c/s. Telephony, two independent sidebands, $M = 3{,}000$ Bandwidth: 6,000 c/s.	6A3 3A3A 6A3B
Sound broadcasting A3.	$B_n = 2M$ M may vary between 4,000 and 10,000 depending on quality desired.	Speech and music, $M = 4{,}000$. Bandwidth. 8,000 c/s.	8A3
Facsimile, carrier modulated by tone and by keying, A4.	$B_n = KN + 2M$ $K = 1.5$	The total number of picture elements (black plus white) transmitted per second is equal to the circumference of the cylinder multiplied by the number of lines per unit length and by the speed of rotation of the cylinder in revolutions per second. Diameter of cylinder = 70 mm Number of lines per mm = 5. Speed of rotation = 1 r.p.s. $N = 1{,}100$. $M = 1{,}900$ Bandwidth: 5,450 c/s	5.45A4
Television (visual and aural) A5 and F3.	Refer to relevant CCIR documents for the bandwidths of the commonly used television systems.	Number of lines = 525 Number of lines per second = 15,750 Video bandwidth 4.2 Mc/s. Total visual bandwidth 5.75 Mc/s. FM aural bandwidth including guard bands: 250,000 c/s. Total bandwidth. 6 Mc/s.	5750A5C 250F3
Composite transmission, A9	$B_n = 2M$ (double sideband).	Television relay, video limited to 4 Mc/s, audio on 6.5 Mc/s FM subcarrier, subcarrier deviation = 50 kc/s. M = subcarrier frequency plus its maximum deviation = 6.55×10^6. Bandwidth 13.1×10^6 c/s.	13,100A9
Composite transmission, A9.	$B_n = 2M$ (double sideband)	Microwave relay system providing 10 telephone channels occupying baseband between 4 and 164 kc/s $M = 164{,}000$. Bandwidth 328,000 c/s.	328A9

Table 5-2. Emission Bandwidth, Frequency and Pulse Modulation

Description and class of emission	Necessary bandwidth in cycles per second	Examples: Details	Examples: Designation of emission
FREQUENCY MODULATION			
Frequency-shift telegraphy F1.	$B_n = 2.6D + 0.55B$ for $1.5 < \frac{2D}{B} < 5.5$ $B_n = 2.1D + 1.9B$ for $5.5 < \frac{2D}{B} < 20$	Four-channel time-division multiplex with 7-unit code, 42.5 bauds per channel, $B = 170$, $D = 200$; $\frac{2D}{B} = 2.35$, therefore the first formula in column 2 applies. Bandwidth 613 c/s.	0.6F1
Commercial telephony F3	$B_n = 2M + 2DK$ K is normally 1 but under certain conditions a higher value may be necessary	For an average case of commercial telephony, $D = 15{,}000$ $M = 3{,}000$. Bandwidth: 36,000 c/s.	36F3
Sound broadcasting F3.	$B_n = 2M + 2DK$	$D = 75{,}000$, $M = 15{,}000$ and assuming $K = 1$. Bandwidth: 180,000 c/s.	180F3
Facsimile. F4	$B_n = KN + 2M + 2D$ $K = 1.5$	(See facsimile, amplitude modulation.) Diameter of cylinder = 70 mm. Number of lines per mm = 5. Speed of rotation = 1 r.p.s. $N = 1{,}100$ $M = 1{,}900$ $D = 10{,}000$ Bandwidth. 25,450 c/s.	25.5F4
Four-frequency duplex telegraphy. F6	If the channels are not synchronized, $B_n = 2.6D + 2.75B$ where B is the speed of the higher speed channel If the channels are synchronized the bandwidth is as for $F1$, B being the speed of either channel.	Four-frequency duplex system with 400 c/s spacing between frequencies, channels not synchronized, 170 bauds keying in each channel, $D = 600$, $B = 170$ Bandwidth. 2,027 c/s.	2.05F6
Composite transmission F9	$B_n = 2M + 2DK$	Microwave relay system providing 240 telephone channels occupying baseband between 60 and 1050 kilocycles. $M = 1.05 \times 10^6$ $D = 2.35 \times 10^6$ Bandwidth. 6.8×10^6 c/s.	6800F9
Composite transmission F9	$B_n = 2M + 2DK$	TV microwave relay, aural program on 7.5 Mc/s subcarrier, subcarrier deviation plus or minus 150 kilocycles. M = subcarrier frequency plus maximum deviation $(7.5 \text{ plus } 0.15) \times 10^6$ $D = 1 \times 10^6$ (visual) plus 0.3×10^6 (aural) Bandwidth. 17.9×10^6 c/s	17,900F9
Composite transmission F9	$B_n = 2M + 2DK$ $K = 1$	Stereophonic FM broadcasting (U.S. system) with multiplexed subsidiary communications subcarrier, $M = 75{,}000$, $D = 75{,}000$ Bandwidth 300,000 c/s	300F9
PULSE MODULATION			
Unmodulated pulse P0	$B_n = \frac{2K}{t}$ K depends on the ratio of pulse duration to pulse rise time. Its value usually falls between 1 and 10 and in many cases it does not need to exceed 6	$t = 3 \times 10^{-6}$, $K = 6$ Bandwidth 4 × 10^6 c/s.	4000P0
Modulated pulse P2 or P3	The bandwidth depends on the particular types of modulation used, many of these being still in the development stage	....	....
Composite transmission P9	$B_n = \frac{2K}{t}$ $K = 1.6$	Microwave relay, pulse-position modulated by 36-channel baseband, pulse width at half amplitude = 0.4 microseconds Bandwidth 8 × 10^6 c/s	8000P9

The value so determined should be used when the full designation of an emission is required. However, the necessary bandwidth so determined is not the only characteristic of an emission to be considered in evaluating the interference that may be caused by that emission.

In the formulation of Tables 5-1 and 5-2, the following terms have been used:

B_n = Necessary bandwidth in cycles per seconds (Hertz)

B = Telegraphic keying speed in bauds

N = Maximum possible number of black plus white elements to be transmitted per second in facsimile and television

M = Subcarrier frequency in cycles per second (Hertz)

D = Half the difference between the maximum and minimum values of the instantaneous frequency. Instantaneous frequency is the rate of change of phase

t = An overall numerical factor that varies according to the emission and that depends upon the allowable signal distortion

Upper and lower limits of an occupied bandwidth are set at the points above and below which only 0.5 percent of the total mean power is radiated. In some cases, for example, in multi-channel frequency-division systems, the percentage of 0.5 percent may lead to certain difficulties in the practical application of the definition of occupied and necessary bandwidth. In such cases a different percentage may prove useful.

An intrinsic requirement for bandwidth is the width of the signal spectrum that must be preserved to make the sampled signal waveform reproducible with a sufficiently low error rate. Because of the response characteristics of physical networks and frequency instability, additional frequency bandwidth or guard space is required. Total frequency space assigned to a channel includes the occupied bandwidth plus guard space.

Saturation Broadcasting

Ideological as well as technological factors are contributing to pressures on the radio spectrum. High-frequency broadcasting is being influenced by developments in electronic technology and geopolitical concepts through the appearance of high-powered broadcast stations in some of the most valuable portions of the spectrum. Advanced-design broadcast stations of up to 500 kilowatts are coming on the air, using high-gain antennas and not necessarily conforming to international frequency allocations. Their broadcast activities may be accompanied by high-powered jamming from nations of different policical bent. The response to the jamming is to put more broadcast transmitters of higher power on the air. Multiple transmitters spaced at 10 kHz intervals over large segments of the spectrum are often used to saturate the spectrum.

The compatibility engineer deplores this sort of activity as contributing to spectrum pollution. The compatibility problem is increased by the fact that in

Region I (Europe and Africa), allocations permit broadcast services in HF and LF bands assigned to aeronautical, amateur, and maritime services in Region II (North, Central, and South America).

CONCLUSIONS

The radio spectrum is a limited natural resource. The right to use a resource is accompanied by responsibility for its wise use. Unlike most other natural resources, the radio spectrum is not exhausted or consumed, but careless or inefficient use can contaminate it and preclude obtaining maximum benefits from it. The goal of compatibility engineering is to permit optimum use of the spectrum through equipment design and frequency allocation. The day is long past when a device employing electromagnetic emission could find an unoccupied segment of the spectrum. Additional devices calling for frequency assignments can be accommodated in the face of growing density of spectrum use only by considering operational compatibility from the inception of the system. Therefore, the task of compatibility engineering can be summarized by saying that the electromagnetic compatibility requirements of an equipment or system must satisfy two conditions: (a) The design compatibility of the equipment or system must assure that, within specified tolerances, it generates no unwanted electromagnetic radiation and is not susceptible to unwanted electromagnetic radiation of other systems or devices, and (b) the operational compatibility of the equipment or system shall be designed so that, within specified tolerances, the intended radiation or reception of electromagnetic energy can be accommodated in a spectrum containing other activities.

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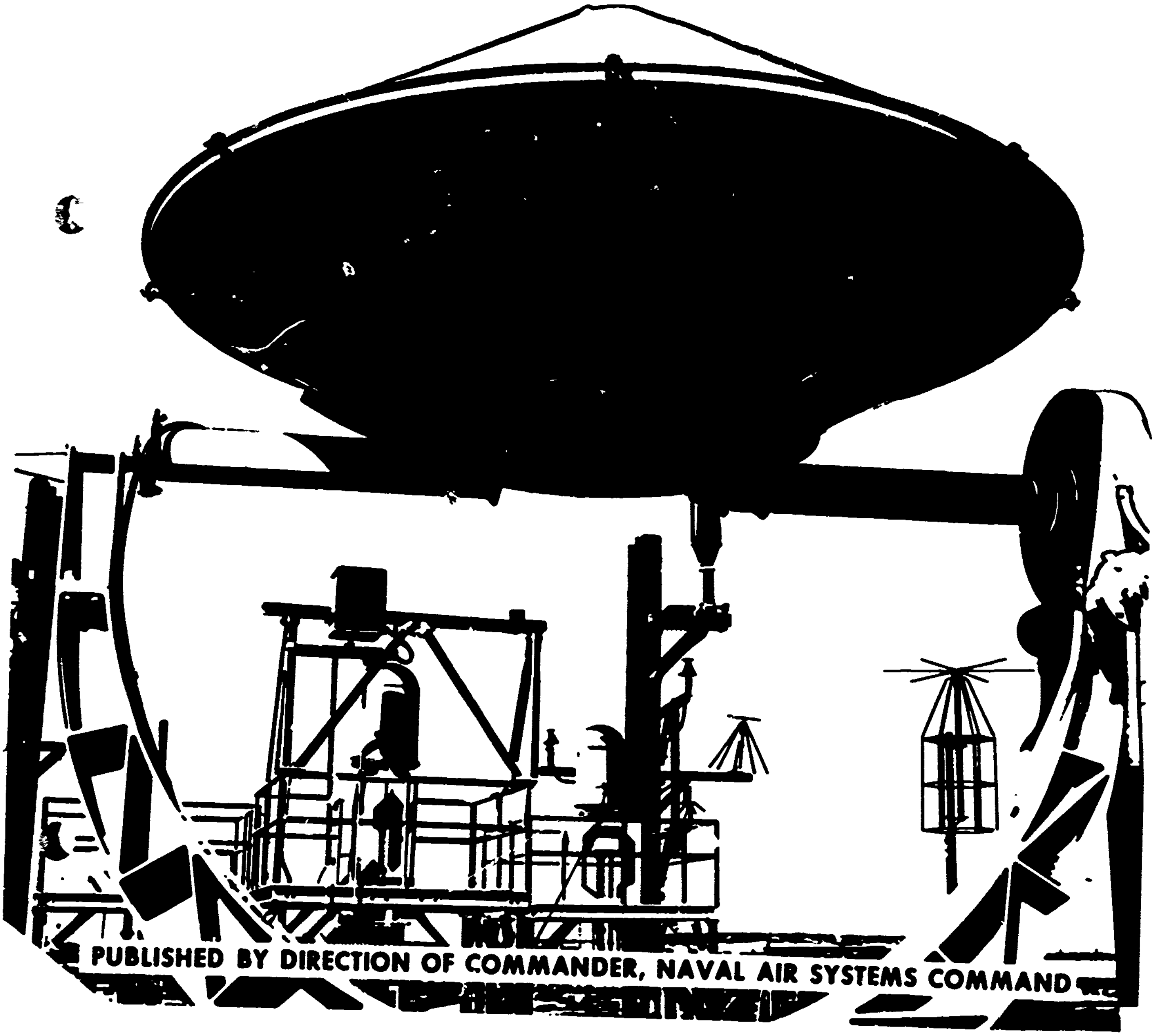
NAVAIR 5335

NAVAL AIR SYSTEMS COMMAND

ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 6



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CHAPTER 6
PRINCIPLES OF ELECTROMAGNETIC INTERFERENCE

CONTENTS

ILLUSTRATIONS

TYPES OF ELECTROMAGNETIC INTERFERENCE (EMI)

The purpose of this chapter is to introduce the concept of electromagnetic compatibility (EMC) and to create an awareness of the magnitude of the EMI problem. Interference problems can affect many things. A home radio may be affected by atmospheric noise or the vacuum cleaner, while the complex problem of finding a suitable frequency and system design for the projected development of a space technology system may also be made more difficult by EMI. EMI effects are evident in homes, offices, plants, ships, aircraft, and almost any place where electrical energy is used. This chapter discusses the sources of EMI energy, defines the characteristics of different types of EMI, reviews the modes of EMI transmission, and discusses susceptible equipments and the effects of EMI upon them.

EMI can produce effects ranging from minor annoyance to complete failure of a mission. This problem is becoming acute because of the continual increase in the number of electronic equipments operating within a given geographical and spectral environment, the high power levels associated with many electromagnetic sources, and the increased sensitivity of equipments that are susceptible to electromagnetic energy. Because of the severity of the EMI problem, frequency coordinators, project managers, system planners, equipment designers, test engineers, maintenance technicians, and equipment users must have adequate knowledge of the technical aspects of EMI generation and susceptibility mechanisms.

For purposes of analysis, three categories of EMI have been devised based upon their source. The first category consists of functional sources; that is, sources that are designed to generate electromagnetic energy and that create interference as a normal consequence of their operation. Examples of the first category are oscillators, communication transmitters, navigation beacons, and radar transmitters. The second category consists of incidental sources; that is, man-made sources that are not designed specifically to generate electromagnetic energy, but which do, in fact, cause interference. Examples include power lines, generators, motors, switches, and relays. The third category consists of natural sources such as thunderstorms, solar and cosmic radiation, triboelectric and precipitation static.

The nature of electromagnetic interference originating from different sources can vary considerably depending upon bandwidth. In this discussion, and

for design and measurement considerations EMI can be classified as broadband or narrowband. Broadband (or wideband) interference includes impulse noise, thermal noise, shot noise, and other nonsinusoidal interference whose energy is distributed over a spectrum of frequencies that is wide when compared with that of the susceptible device, filter, or measurement equipment through which it is processed.

Narrowband interference includes CW signals, modulated or unmodulated carriers, or other largely sinusoidal signals whose energy is distributed over a spectrum of frequencies not greater than the bandwidth of the circuit or device through which it is processed. For example, sources such as oscillators or transmitters that generate electromagnetic energy may produce a single-frequency sine wave, a relatively narrowband amplitude or frequency modulated signal, or a pulse type of signal.

In general, the functional energy originating from these sources will be coherent and predictable, with its energy confined to specific frequencies or ranges of frequencies. These characteristics constitute the spectrum signature of a particular piece of equipment. On the other hand, incidental electromagnetic sources often generate energy that is spread over a very wide portion of the spectrum. In many instances, the interference can be controlled or eliminated at the source of generation. In other cases, it must be controlled at the receptor of the interference.

The simplest form of a functional signal is the single-frequency sine wave. However, even though some equipments such as oscillators and beacons are designed to produce these single-frequency sine waves, equipment instabilities and nonlinearities will result in spurious energy being present in a narrow band around the fundamental and at harmonic frequencies. The energy bandwidth and the harmonic content of these sine wave sources can be controlled by stabilizing the operation and restricting the nonlinearities.

In more complex systems such as communication or radar transmitters, the processing of the functional signal often results in the generation of undesired electromagnetic energy at frequencies other than the operating frequency. These spurious outputs are not necessary to the proper function of the system, therefore it is desirable to eliminate them or reduce their amplitude as much as practicable.

FUNCTIONAL SOURCES OF EMI

Certain electromagnetic equipments such as communication, radar, and control transmitters are designed to produce electromagnetic energy. Because the signals generated by these equipments are necessary, they cannot be eliminated without making the equipment useless. Because many such signals will be present in any operational military environment, it may be helpful to review briefly the characteristics of these signals and investigate methods to reduce their EMI potential.

In developing an electromagnetic signal output intended to serve a functional purpose, a transmitter may radiate through the equipment case as

well as from the antenna, spurious energy capable of causing interference. A transmitter may also emit conducted EMI through the attached cables. The spurious emission may be a consequence of normal signal processing within the transmitter as in frequency multiplication, mixing, or amplification in Class C amplifiers, or it may be a result of design deficiencies or improper operation as in sideband splatter, parasitic oscillation, or amplified circuit noise.

EMI Attributed to Fundamental Functional Signals

Functional EMI sources are those designed to generate a specific frequency or frequencies to perform a function. The spectrum occupancy of the fundamental signal is an inherent part of system operation and means must be found to fit it into the environment it must share with other emissions. Therefore, potential EMI from functional sources is controlled first in frequency allocations and power restraints. Project engineers and designers of electromagnetic systems must predicate their system design on the availability of a frequency assignment for the desired functional signal. It is a waste of time, talent, and resources to proceed into the hardware fabrication stage before being assured that a suitable frequency channel for the functional signal is available and is compatible with the environment.

System designers should try to avoid placing an equipment on the same frequency or one closely related, with which mutual interference will be a problem. This includes avoiding frequency combinations that will put harmonics or unwanted mixer products on the same frequency as that of susceptible RF or IF amplifiers of other nearby equipments. If the system occupies an appreciable frequency range, as most of them do, it is unlikely that the designer can avoid all such combinations, however.

A functional signal can sometimes be made compatible with its electromagnetic environment if the system designers exercise power restraints. A low-level transmitter, with a compensatory high-gain antenna at the receiving end of the path, can be accommodated in portions of the spectrum where a high power transmitter cannot be tolerated.

EMI problems that cannot be solved conveniently through frequency selection and power restraints may be corrected through use of time-sharing. For example, an interfering functional signal may be blanked or inhibited briefly while a computer data link receives updating inputs, or two radars may be pulsed alternately or in exact synchronism to avoid mutual interference.

EMI Attributed to Modulation Bandwidth

Electromagnetic compatibility and spectrum conservation require that careful attention be given to the selection of the frequency bandwidth of each equipment. Bandwidth requirements are determined by the transmission characteristics of the functional signal. To conserve the electromagnetic spectrum, the bandwidth of a system should be no wider than necessary to provide for the best use of the spectrum. On the other hand, if the selected bandwidth is too narrow, rigid rise-time restrictions will be imposed on the

system and the designer may not be able to satisfy operational requirements.

There is an interrelation between modulation bandwidth and power restraints for some types of modulation. For example, an increase in the modulation bandwidth of an FM communication link or a chirp radar makes it possible to reduce the radiated power while retaining system effectiveness.

Necessary bandwidths required for different types of modulation were described in Chapter 5. Once a particular type of modulation has been selected and a channel assignment obtained for that modulation bandwidth, it is a design obligation to avoid excessive modulation bandwidth because of its EMI potential. Energy beyond the bandwidth necessary for the functional signal can produce electromagnetic interference with other systems.

One type of spurious emission that may occur in developing a functional signal is excessive modulation bandwidth. In general, modulation splatter broadens the bandwidth of the transmitted signal. Modulation splatter in amplitude-modulated transmitters occurs when excessive modulation depth causes the carrier to be cut off abruptly on negative modulation peaks. Modulation splatter can also be caused by "flat-topping" of AF or RF amplifiers on positive modulation peaks. Modulation splatter results from such factors as modulation limiters, overdriven amplifiers, nonlinearities in the modulation, and poor power supply regulation. In single-sideband (SSB) transmitters, splatter is most often caused by overdriving an RF amplifier so that it operates in a non-linear region. Overmodulation of frequency-modulated transmitters causes the frequency swing to exceed its maximum allowed deviation, resulting in excessive bandwidth. With pulse systems, appreciable amounts of splatter can be generated if the modulation waveshapes have very fast rise times.

The average modulation index of a transmitter can be raised by amplifying the weaker components to a level where they can modulate the transmitter more fully, then clipping or compressing the modulation peaks to keep them from causing over-modulation. For speech waveforms, 10 dB of peak clipping allows a communication effectiveness comparable to 10 dB higher average power output. Therefore, modulation peak clipping not only offers a way to avoid overmodulation and consequent EMI from that cause, but is also conducive to power restraints. Transmitter power may be reduced by peak clipping. However, peak clipping can produce the same splatter effect as unintentional flat-topping or overmodulation unless the design contains filters to remove the splatter components generated by the nonlinearities.

Modulation peak clipping must be applied to the audio or video amplifiers of conventional AM or FM transmitters before modulation. For SSB transmitters, a different technique is necessary. Linearity must be maintained until modulation occurs in a low-level stage. The low-level modulated stage should have a carrier input many times the amplitude of the modulating signal so that overmodulation cannot occur. The carrier is then suppressed, usually at the output of the modulated stage. Amplitude peak limiting is then applied to the resultant modulated RF signal. As in AF limiting, suitable filters must follow the limiting process to remove the products caused by nonlinearity. The alternative to amplitude peak limiting is automatic level control (ALC), which reduces the

gain of speech amplifiers or low-level modulated stages enough to prevent any stage from being driven into nonlinearity on modulation peaks.

EMI Attributed to Harmonics and Mixer Products

In almost all transmitters, direct harmonics of the output frequency are present as a result of nonlinearities in the power amplifier. Transmitters that use frequency multiplication to generate the functional output may also have spurious outputs at frequencies that are multiples of the basic frequency of the oscillator and of harmonic amplifiers.

The spectrum shown in Figure 6-1 represents the output of a typical communication transmitter that uses a master oscillator followed by frequency multiplication and power amplification to generate the funcational output. In this figure, the harmonic outputs, which are integral multiples of the functional output, are seen. Additional outputs that are harmonics of the master oscillator also appear. Some of the master oscillator harmonics are deliberately accentuated and amplified in the frequency multiplier(s) to drive the power amplifier at the desired output frequency. Frequency multiplication in the power amplifier is highly undesirable. However, a certain popular UHF Navy transmitter (TDZ sets), which triples the power amplifier continues in use despite its violation of good EMC design practice.

A transmitter using a frequency synthe[illegible]er to develop a functional output has a much more complex spectrum. Such transmitters use two or more oscillators, and process their frequencies through multipliers, dividers, and

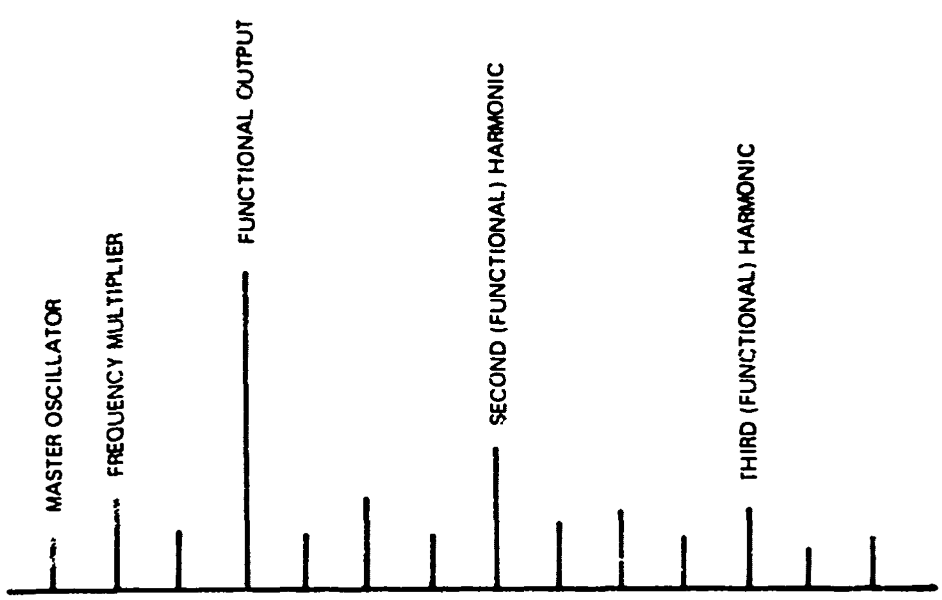


FIGURE 6-1 TYPICAL SPECTRUM OF A FREQUENCY-MULTIPLIER TYPE TRANSMITTER

mixers to synthesize the fundamental output frequency. A representative avionic transmitter of this type is the AN/ARC-27 or -52 series. These transmitters start with an oscillator having selectable 0.1 MHz frequency intervals and heterodyne its output against a second oscillator with frequencies selectable at 1.0 MHz intervals. The desired mixer product is amplified and heterodyned against an oscillator with frequencies selectable at 10 MHz intervals. A fourth mixing step is needed to reach the UHF output frequency. The output frequency is thus synthesized from a series of mixer products. The frequency increments of 0.1, 1.0, 10, and 100 MHz represent steps in the fundamental output frequency: the actual crystal oscillator frequencies are a fraction of these values and harmonic amplifiers are used for frequency multiplication to the desired output. The spectrum of such a transmitter will contain the fundamental and harmonics of all the oscillators, all the mixer cross-products and their harmonics, and all the harmonic contributions of nonlinear amplifiers that include the frequency multipliers and power amplifier. The power level of each of these products depends upon the degree of accentuation and attenuation it receives on being processed through the transmitter: only one of them is the desired functional output, and the rest are spurious.

EMI Attributed to Transmitter Noise

A transmitter may radiate sufficient spurious noise to interfere with a nearby receiver, even one tuned to a widely separated frequency. Chapter 15 of this manual discusses the noise contribution of parts such as resistors, tubes, and transistors to the circuits in which they are used. While it is common to think of the noise generated by circuit parts in terms of receiver design, noise is also pertinent to transmitter spurious emission. Ordinarily, the noise content of the transmitter output is many decibels below the functional output and is not serious at the intended receiver. However, transmitter noise has a wide spectrum distribution that can cause interference to non-related receivers nearby.

EMI Attributed to Transmitter Parasitics

Parasitic oscillation results when some part of the transmitter, usually the power amplifier, breaks into oscillation at a frequency determined by the normal input-output tuned circuits, or at the frequency of some stray circuit resonance. The frequency-determining element for stray-resonance parasitic oscillation may be a straight wire, a resistor, an RF choke, a capacitor, tube structural elements, transistor transit time, or almost any circuit part or combinations thereof. It is not uncommon for a stage thought to be "clean" to break into parasitic oscillation on modulation peaks. Because of the wide variety of parts and combinations that can participate in spurious oscillation, the resultant spurious emission may be of any frequency from VLF to SHF. This type of oscillation is almost always highly unstable in frequency modulation.

INCIDENTAL SOURCES OF INTERFERENCE

There are many electrical or electronic devices such as DC motors, neon

signs, ignition systems, and high tension lines that are designed for some function other than to generate electromagnetic energy but which produce EMI as an incidental by-product. Because these parts or equipments are not designed to generate electromagnetic energy, it is often possible to reduce or eliminate the EMI they produce without impairing the normal function of the device.

The frequency spectrum associated with incidental sources is often extremely wide. In addition to being broadband in the frequency domain, the interference can be further classified as random or impulsive, depending upon the time domain.

Random EMI

Random interference results from such factors as thermal agitation and current flow disturbances that produce interference with random amplitude characteristics. Certain natural types of interference such as atmospheric noise, cosmic noise, and solar noise resemble random interference in that the impulses are frequent and overlap with a number of sharp peaks exceeding the average level.

Impulse EMI

Impulse interference is produced by one or a series of electromagnetic pulses of short duration relative to a cycle at the highest frequency being considered. The spectral intensity is proportional to the volt-time area of the impulses, and is uniformly and continuously distributed through the spectrum up to the highest frequency at which it may be considered an impulse.

The characteristics of impulse interference will be modified by the receptor through which the impulses are processed, unless the receptor bandwidth is at least equal to that of the interference. Impulse interference will shock-excite a bandwidth-limiting receptor into overshoots and post-impulse ringing so that the spectral distribution and time duration of the interfering energy is altered. If the duration of post-impulse ringing is approximately that of the interpulse period, then no clear separation of pulses is evident. Examples of impulse interference sources are electrical ignition systems, high-tension power line leakage, vacuum cleaners, thermostats, and other electrical and electromechanical devices producing abrupt changes in current or voltage.

In general, the frequency spectrum associated with either random or impulse interference is extremely broad. Because the interfering energy is spread over a wide spectrum, the effective magnitude of the interference power is a function of the bandwidth of the receiving or measuring receptor. To relate the level of broadband interference to receptor bandwidth, the magnitude is generally specified in terms of milliwatts (or watts) per kilohertz of bandwidth.

Figure 6-2 shows typical levels associated with various types of natural and incidental interference. These levels are given in terms of peak radiated field strength levels. All curves assume a bandwidth of 10 kilohertz. The noise amplitude varies as the square root of bandwidth except for the man-made noise curves. The nature of man made noise is so variable that there is no method of

accurately adjusting to bandwidths other than 10 kHz. For example, the amplitude of the field strength radiated by a dielectric heating device will be the same in a 100 kHz or 10 kHz bandwidth receiver. However, the peak-noise field strength of a commutator type motor will increase in some direct relationship to bandwidth.

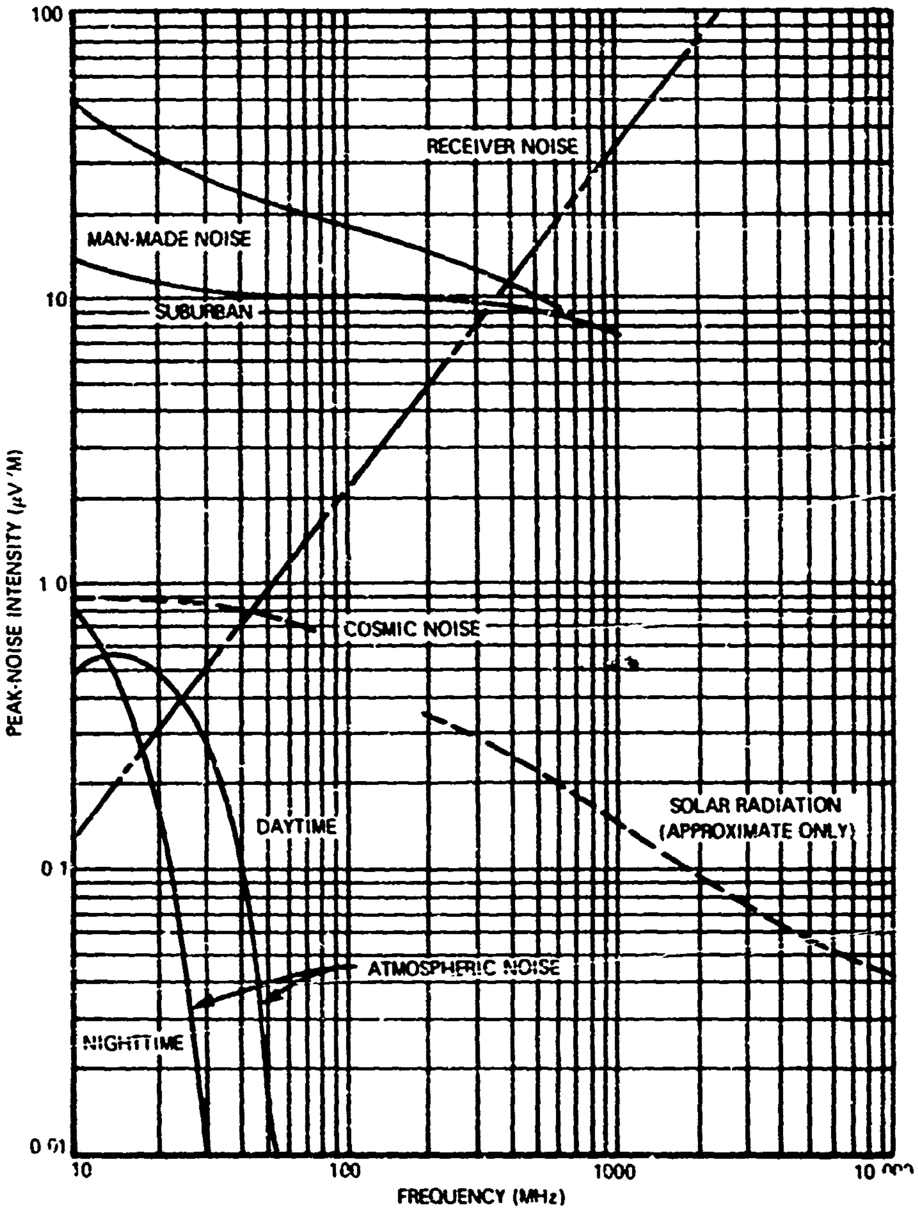


FIGURE 6-2 TYPICAL INCIDENTAL INTERFERENCE LEVELS

There are many man-made electrical and electronic devices that can produce broadband incidental EMI. Usually, the amplitude of radiated EMI of these devices is low so that it may not interfere with other equipment located in the same aircraft. However, many of these incidental EMI devices are connected directly to the power distribution system so that direct coupling into other equipments may be a serious problem unless decoupling measures are used.

Industrial, Scientific, and Medical EMI Sources

RF-stabilized arc welders and medical and industrial heating equipments are potentially serious sources of interference. However, the amount of radiation from these sources on other than the assigned frequencies is controlled by the Federal Communications Commission. On the assigned frequencies of 13.56, 27.12, 40.68 and 915 MHz as well as 2.45, 5.8 and 22.125 GHz, no radiation limitations are specified. Although these controls apply only in the United States, a number of other countries have comparable regulations.

Diathermy equipment usually operates at either 27.12 MHz or 2.45 GHz, assigned frequencies for unlimited radiation. Spurious and harmonic radiation outside of these frequency bands must b limited to a strength of 25 μv/M at a distance of 1000 feet or more. If, for any reason, the diathermy equipment must be operated at a frequency other than one of those assigned, and the radiated level will exceed 25 μv/M at a distance of 1000 feet, then the installation must include sufficient shielding and use operating procedures that will insure that FCC regulations are not violated.

Many electric arc welders use radio frequency energy to maintain or stabilize the arc during welding. This creates a train of distorted square wave pulses that may persist for several seconds. The resulting broadband spectrum is concentrated in two ranges, a lower range between 10 and 100 kHz and an upper range between 0.5 and 100 MHz. The resulting interference can be intense and capable of extensive geographic saturation. The FCC regulations require that the operator of the arc welding equipment take remedial action if there is interference to any authorized radio service. This will generally require that the arc welding equipment be operated within some type of shielded enclosure.

EMI From Illumination Sources and Gaseous Tubes

Fluorescent tubes, neon signs, and mercury or sodium lamps, as well as gaseous tubes such as rectifiers and regulators used in electrical and electronic equipments are sources of prolific wideband interference. A similar type of interference can be generated by the face of cathode ray tubes used for display purposes. Because of the interference caused by these sources, their interference levels should be considered in the design of a particular equipment or system, but it is not generally necessary to consider these sources outside of the particular ship or aircraft of which they are a part.

Fluorescent and gaseous lighting devices produce interference that seems more confined geographically than either ignition or power transmission-line noise. Gaseous discharge interference is typically a train of damped oscillations

following excitations at powerline frequencies, with oscillation frequencies exceeding 100 kHz. Because of its confinement to local radiation fields and coupling through the power system, gaseous discharge interference is mainly a threat to electromagnetic systems in the ship or aircraft in which the interference is generated. Where significant, this type of interference can be suppressed at the source with a simple and inexpensive filter.

EMI Caused by Rotating Electrical Machinery

Rotating electrical machinery such as drive motors, blower motors, generators, dynamotors, and rotary converters can generate wideband interference. The EMI is largely the result of current switching in the commutation process or of starting current surges. Unless the housing of the rotary machinery makes a satisfactory shield, radiated energy can cause interference locally. Because the interference is coupled to the power line to which the rotary electrical machinery is connected, the interference can also be conducted to other devices in the same power system.

EMI Caused by Electrical Ignition Systems

Spark-fired ignition systems, such as those used by piston engines and by jet engine starters, are sources of high-level impulse interference. The ignition system is a high-voltage arc device that originates interference at the breaker points, rotor gap, and spark plugs. The interference can be conducted by electric wiring (including ammeter and ignition switch leads), engine instrument gauge wires, or mechanical linkages such as choke or throttle controls. The interference can also be radiated by these same devices, by the ignition wires, and by the engine block and exhaust system, especially when bonding across rubberized shock or vibration mounts is inadequate.

At the present time, commercial manufacturers of automobile, truck, and marine engines are not subject to EMI control regulation in the United States, and the ignition systems of these engines make a major contribution to the urban EMI levels. As a result of automative ignition noise, urban EMI levels at 100 MHz have been increased by a factor of 1000, or 30 dB. When spark-fired engines must be used near susceptible communication equipments, extensive noise-suppression must be applied to the ignition system.

EMI Caused by High-Tension Lines

Power lines can generate EMI, usually as the result of current leakage across insulators or of corona discharge to the atmosphere. High-voltage transmission lines and high-voltage generation equipment produce detectable RF noise that reaches maximum intensity in rain, snow, fog, and high relative humidity. In addition to their ability to generate EMI, power transmission lines also conduct and radiate interference generated by the devices that are connected to the power distribution system.

When power transmission lines and components have deteriorated or have been damaged, their impulsive noise emission above 50 MHz rises appreciably and is readily detectable in the absence of intense ignition noise. The waveform of power transmission noise is impulsive but generally of greater pulse width and less frequent occurrence than ignition noise. Typically, the interference occurs in bursts of several milliseconds. The fine structure of the burst pulses consists of short-duration, fast rise-time, distorted square waves occuring often at high repetition rates. Very-wide-band receivers have recorded powerline pulse durations and rise times of 10 to 20 nsec. Their origin has been identified as actuations of inductive loads on the lines. Reliable reports associated the shortest-duration transients with corona discharges on the lines and support elements. These discharges were a result of line imperfections due to component aging and damage. Interburst repetition periods for both sources were comparable to the pulse durations. Analysis of the resulting noise spectra shows that it extends to the VHF region.

Power lines can support long-distance, low attenuation propagation of high frequency transients because of their ability to function as either coaxial waveguides or as a single line above ground. In addition, transmission lines may resonantly enhance noise spectra peaks. The resonances arise from periodicities in the power line mechanical construction, such as directional changes in runs or support spacing separated by a half-wavelength for particular harmonic components.

EMI Caused by Switching Devices

Switching devices are present in almost all electrical and electronic equipment. Electronic switching devices such as trigger generators, thyratron pulse modulators, power supply rectifiers, and digital logic circuits should be considered, as well as the more familiar mechanical switches and electromechanical relays. Chopper devices such as transistor switches or vibrators used in power supplies or for stabilization of DC amplifiers should appear high on the list. As a general rule, those equipments that require switching large amounts of power are potential sources of serious EMI. When a switch is turned on, the current and voltages in the circuit must make a rapid adjustment from zero to full value. Because all circuits contain capacity and inductance, the change in current and voltage values cannot occur instantly. During the short interval in which current and voltage are changing to a new value, EMI transients are produced. The spectral distribution of the EMI is dependent upon the magnitude of the current, voltage, and impedance of the circuit. The shape and duration of the individual pulses as determined by the current, voltage, and impedances of the circuit give the characteristic spectrum signature to the EMI.

As a general rule, a pulse of very short duration covers a very wide spectrum. The longer the duration of a single pulse, the more of its electrical energy will be found at the low-frequency end of the spectrum. The faster the pulse rises to its peak value, the higher the frequencies generated.

Sparking or arcing of the contacts of switches, relays, and commutators of

various kinds are additional sources of interference. Mechanical conditions that cause and sustain the arc contribute to the interference. For example, in a relay the contact spring tension, contact chatter, armature impact, and the air gap in the magnetic circuit all contribute to the magnitude and duration of the arc at the relay contacts. A brush-type motor or generator consists of a series of switches involved in the commutation process and therefore can be a prolific source of EMI.

NATURAL INTERFERENCE SOURCES

The effects of natural interference sources are identical to those of man-made sources. They generate either random or impulsive broadband noise.

Earth-bound noise/interference effects up to approximately 40 MHz are primarily attributed to lightning discharges in the atmosphere. Local natural interference sources are also important. These include snowstorms and dust of volcanic origin as well as wind-driven sand and dust. Precipitation noise originating on an antenna or in its near field may reach sufficient magnitude to make a receiver useless.

The predominant natural source of radio noise, from very low audio frequencies up to about 40 MHz, is now widely accepted as lightning discharges originating from thunderstorm cells. Greatest spectral density of radiated energy occurs at frequencies below 100 kHz, with a broad maximum at about 5 kHz and an approximate $1/f^2$ decrease at higher frequencies. Intense lightning discharges give rise to whistlers, which are a small part of the VLF radiation propagated along the lines of the earth's magnetic fields and which cause almost musical sounds in headphones. Geographical regions of greatest lightning-caused radio interference are in the tropics and in mountainous areas of the middle latitudes during the summer. Thunderstorms are almost completely absent in the higher latitudes.

Propagation of atmospheric noise from lightning discharges involves one of several different modes, depending on frequency. At VLF (in the order of 10 kHz) ground wave propagation predominates. At very long ranges, ionospheric wave propagation predominates and waveguide modes of propagation are excited in the space between the earth and the ionosphere. Very long range low loss propagation is possible within the waveguide modes so that the interference is not confined to the area of thunderstorm activity. Propagation of atmospheric noise at MF and HF is assumed to follow the same modes as encountered with conventional communications signals in these frequency ranges.

Precipitation static and lightning is the subject of Chapter 18. Precipitation static is another form of natural interference. It is caused by charged particles such as rain, snow, or ice impinging on a conducting surface such as aircraft, electrically isolated from ground. The aircraft accumulates enough charge to cause corona discharges to occur at sharp projecting points, such as wing and stabilizer tips. The corona produces broadband noise, with discrete bands at VLF frequencies and a relatively continuous spectrum for higher RF frequencies. Little interference from corona is experienced at VHF frequencies

and above. Precipitation static also occurs with the charging of dielectric surfaces.

Charge exchange between sand or dust particles and conducting or dielectric surfaces results in repeated point discharge or streaming effects and corona noise. It behaves in the same way as precipitation static.

Cosmic noise originates outside our solar system. Its frequency spectrum covers 1 MHz to 30 GHz. Cosmic noise may be general background radiation that varies in intensity relative to location in the sky, or discrete bright radio sources with well-defined boundaries and regions of location in the sky. The first type, galactic noise, originates in our galaxy, excluding the sun, and shows a monotonic decrease of power level with increasing frequency, in accordance with an approximately $f^{-2.5}$ law. Extra-galactic noise comes from discrete sources originating primarily from radio stars that show spectral power outputs decreasing at a rate of about 6 dB per octave which is in accordance with an f^{-2} law.

The sun is the primary originator of solar system noise. Thermal and non-thermal generation are both involved. Quiet sun radiation is of thermal origin, covering the whole RF spectrum. At frequencies above 30 GHz, radiation from the sun is essentially that of a black body at 6000°K, the sun's surface temperature. At lower frequencies, however, the radiation temperature of the sun corresponds to the much higher temperature of the outer layers of the solar atmosphere (chromosphere and photosphere). Generally, solar noise remains at a roughly constant radiation level. However, high-intensity noise may be produced by solar disturbances such as sunspots and solar flares. Radiation from the disturbed sun contains a slowly time-varying component in the 500 MHz to 10 GHz frequency band that appears to be directly related to the number and size of sunspots. During very intense solar activity, radio noise storms generate brief bursts of radiation intense enough to cause as much as 60 dB increase in the normal (quiet sun) background radiation level.

INTERFERENCE TRANSMISSION

The two basic modes by which interference can be transmitted from a source to a susceptible equipment are by conduction and radiation. For the purposes of this discussion, it will be considered that the mode of interference transmission is by conduction, if circuit theory can describe the transfer of energy from the source to the susceptible equipment. However, if field theory must be used to describe the transfer of signals, then the mode of transmission is considered to be by radiation.

It is entirely possible for interference to be transmitted by any combination of both methods (as shown in Figure 6-3). For example, interference can be radiated from one equipment, picked up on interconnecting cables of another equipment, and thereafter conducted into the equipment shielded enclosure by the wiring. Conversely, interference can be conducted outside the cabinet or shielded enclosure of the source by cabling, while at the same time it is radiated by the cabinet and wiring.

RADIATED EMI

Every electrical circuit carrying an alternating current radiates some electrical energy in the form of electromagnetic waves. Unless the dimensions of the circuit approach the order of magnitude of a wavelength, the amount of energy radiated from a circuit is small relative to the energy available in the circuit. Because wavelength is inversely proportional to frequency, high-frequency waves can be radiated by a small radiator, while low-frequency waves require a large radiator.

All radiators tend to radiate more energy in certain directions than in others. Antennas are devices designed primarily to radiate or receive electromagnetic energy and they are often intentionally made highly directional. This property can be used for EMI reduction by orienting an antenna so that a null faces the EMI source, or so that a lobe faces an intended path.

Although all circuits that carry an alternating current can radiate some electromagnetic energy, circuits not designed to act as antennas are not generally very efficient radiators or receptors. Therefore, interference radiated or picked up unintentionally by power lines, cables, or mechanical parts generally presents an interference problem only within a relatively small region surrounding the radiator. On the other hand, antennas are efficient radiators or receptors of electromagnetic waves and electromagnetic energy they radiate or receive can produce interference in a susceptible equipment at an appreciable distance. This problem may be further aggravated by highly directional antennas, which tend to concentrate the radiation or reception in a particular direction. Many types of antennas are also efficient radiators at harmonically-related frequencies, so that no dependence should be placed on the antenna for harmonic rejection.

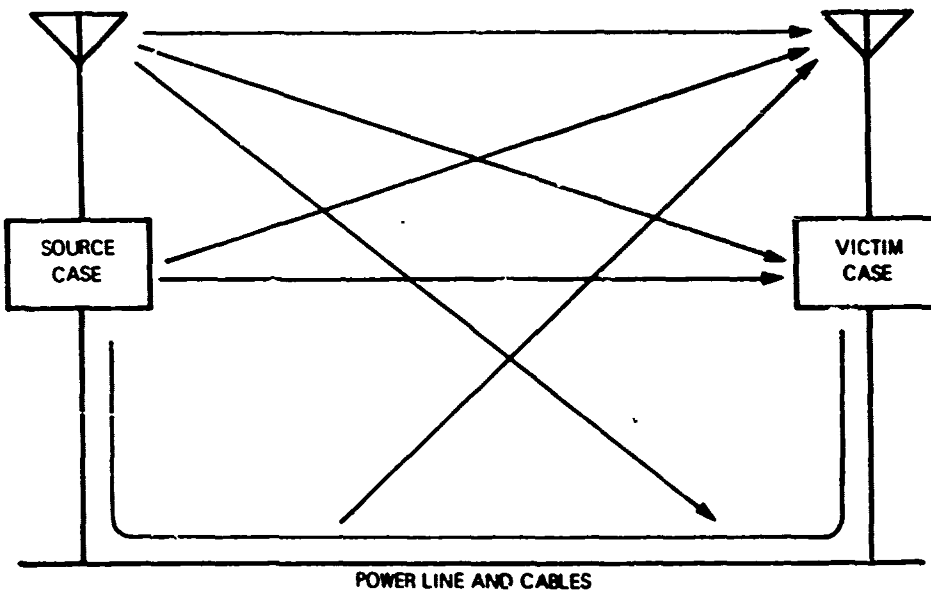


FIGURE 6-3 INTERFERENCE TRANSMISSION METHODS

As electromagnetic waves radiate from their point of origin, they become attenuated due to several factors. First, as the waves travel from the origin they spread out spherically so that their power density is reduced. Second, energy may be absorbed from the waves by the ground or by the ionized regions in the upper atmosphere. Third, waves may be reflected, scattered, or refracted by conditions within the atmosphere or on the ground. If waveguide modes of propagation exist because of surface trapping or ionospheric reflection, the spherical spreading is modified. The resulting situation is quite complex and differs for radiated waves at different frequencies.

Radiated interference levels are generally given as the electrical field strength or power density at the receptor. The levels can be expressed either in terms of volts per meter or watts per square meter. A field level of one volt per meter means that a potential of one volt will be induced in an antenna having an effective electrical length of one meter. A power density level of one watt per square meter means that one watt of available power will be received by an antenna with an effective capture area of one square meter.

Any device that acts as a radiator or receptor of a signal can be considered an antenna and analyzed as such. Therefore, the initial point of analysis would be to consider the properties of the antenna and the properties of the electromagnetic field surrounding it. There are two major components of the electromagnetic field, the electric (E) and the magnetic (H). At a distance from the source, where the field may be considered to consist of plane waves, the relationship between the two fields is expressed as follows:

$$Z_o = \frac{E_o}{H_o} \simeq 377 \text{ ohms (in free space)} \qquad (6\text{-}1)$$

Wherein:

Z_o = impedance of the medium

E_o = magnitude of the electric field

H_o = magnitude of the magnetic field

Equation 6-1 does not apply close to the emitter. A condition involving plane waves is seldom encountered in investigating mutual interference between components of a system. Therefore, to analyze the field and its effects, one must necessarily consider (and measure) the E and H components separately.

Basically, the antenna radiation pattern is subdivided into two major regions, the far field and the near field. The far field contains only transverse E and H components and the relative shape of the pattern does not change with distance from the antenna. It is in this region that the field is principally the radiation field, although radiated EMI considerations also include the effects of the near field. The near field contains both transverse and radial components of E and H. The radial component is an inverse function of the distance from the antenna. The transition between near field and far field is not clearly defined in practical measurements. A formula generally recognized for establishing the transition point is:

$$R = \frac{2D^2}{\lambda} \quad \text{or } R = 3\lambda \tag{6-2}$$

whichever is greater.

Wherein:

D = largest dimension of the antenna
λ = wavelength at the frequency of interest
R = transition distance measured along a line from the antenna

CONDUCTED EMI

Frequently it is necessary to transmit power, operational signals, or control voltages between equipments or components via cables. These cables may carry a number of signals that range from simple DC levels that operate relays or control lights, to wideband pulse and video circuits. It is possible for EMI to be conducted along the cable and be transmitted by it from one equipment to another. Long cables offer an increased opportunity for signals to couple from one wire to another and for interference from external sources to be picked up and conducted by the cable.

Conducted interference is generally specified in terms of decibels relative to the interference current in the line or cable as measured in microamperes (dB/μa). If the interference is broadband, the unit of measurement is dB/μa/MHz. The standard measurement procedure uses a clamp-on type current probe which, in conjunction with a field intensity meter, can make a direct measurement of line current at any desired frequency. The power line is stabilized with a 10 microfarad feed-through capacitor. Older specifications, such as MIL-I-6181D, provided an optional method of measuring conducted interference. A standard line impedance stabilization network (LISN) was inserted in the line to provide a standard 50 ohm impedance. The interference voltage measurement was made across this 50 ohm impedance and limits were specified in terms of microvolts or dB/μv for narrowband interference and microvolts per megahertz or dB/μv/MHz for broadband interference. Both of these methods are readily adapted to power line, control, or signal line type measurements.

Conductive Mutual Coupling

Mutual coupling of EMI is the result of the susceptible circuit sharing a magnetic or conductive path with the interference source. According to circuit theory, the coupling is accomplished either by mutual impedance or by mutual admittance between the two circuits.

An example of mutual impedance coupling is shown in Figure 6-4. A mutual impedance is said to exist when the current flowing in circuit 1 produces a voltage in circuit 2. The magnitude of the mutual impedance is the ratio of the open circuit voltage of circuit 2 (with all other sources of voltage removed) to the current in circuit 1.

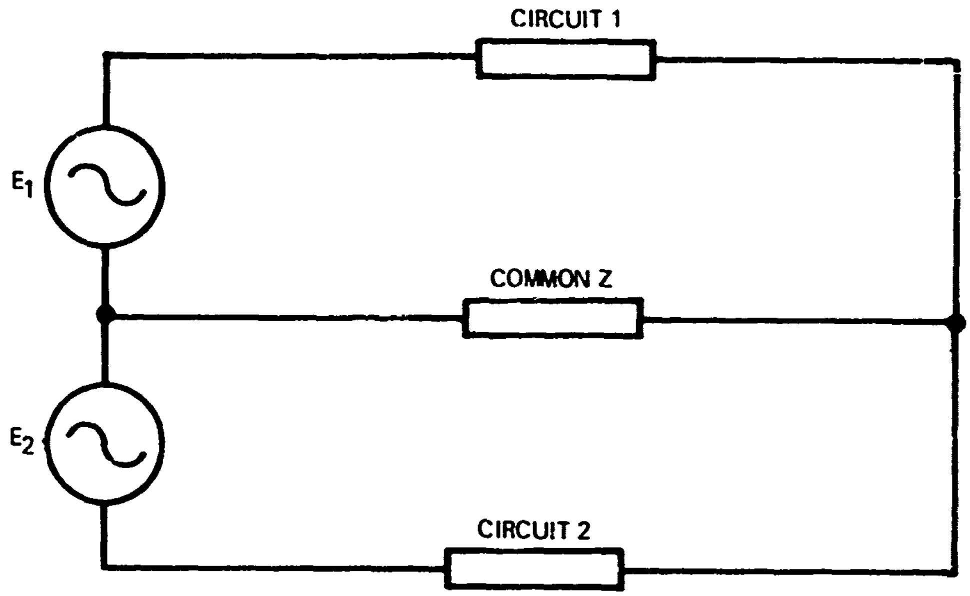


FIGURE 6-4 MUTUAL IMPEDANCE COUPLING

The common impedance may be any circuit element, including structural elements involved in electrical or magnetic currents. Typical examples are:

1. Common ground return impedances, including chassis grounds and cabinet bonds and ground straps. At RF, the length and impedance of a ground path is likely to be greater than that for DC because of skin effect and other frequency-related effects.

2. Common power supply impedances, including distribution cables and decoupling networks. A power supply system having satisfactory performance at low frequencies may be unsatisfactory from the high-frequency EMI standpoint.

Mutual admittance coupling as shown in Figure 6-5 is said to exist when a voltage in circuit 1 produces a current in circuit 2. Figure 6-6 illustrates admittance coupling of EMI through mutual capacitance. Mutual capacitance exists between any two conductors. Examples include two wires in a cable harness, the plate of a vacuum tube and other circuit elements inside and outside the tube envelope, or two windings of an inductor. Considering the EMI, the mutual capacitance coupling is that existing between a circuit containing an EMI source and a circuit containing susceptible elements. Capacitive coupling of EMI occurs because changes of potential difference due to EMI disturbances force corresponding charge-discharge currents to flow in the susceptible circuit.

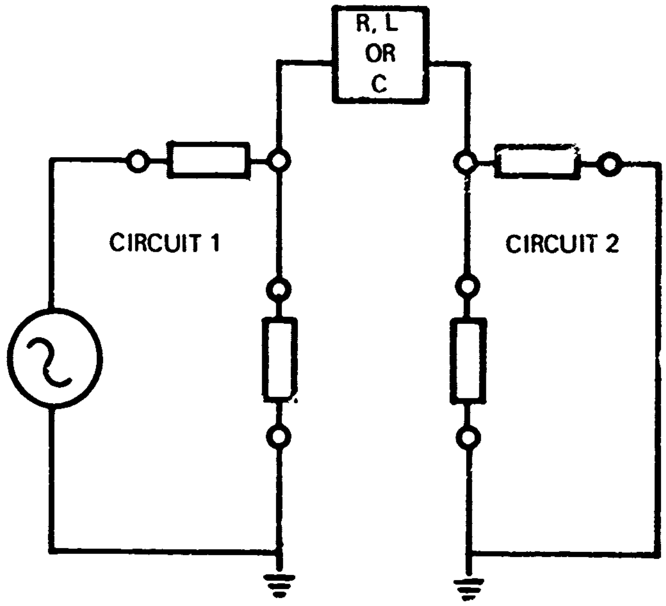


FIGURE 6-5 MUTUAL ADMITTANCE COUPLING

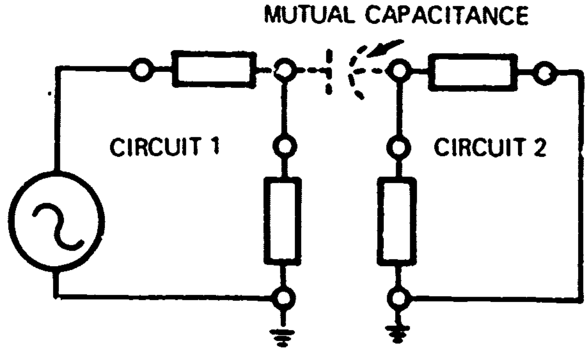


FIGURE 6-6 MUTUAL CAPACITANCE COUPLING

Inductive Mutual Coupling

Mutual inductance coupling, as shown in Figure 6-7, results when the magnetic field created by currents flowing in circuit 1 links with circuit 2 and thereby induces a voltage into it. The magnitude of the induced voltage can be shown by the following formulas:

$$\phi = Mi \qquad (6\text{-}3)$$

$$E = \frac{d\phi}{dt}$$

$$E = (M)\frac{di}{dt}$$

Wherein:

ϕ = magnetic flux

M = coefficient of mutual inductance

i = current in circuit 1

E = voltage induced in circuit 2

The voltage produced is proportional to frequency because E = IZ and Z = $j\omega M$, where E = voltage in circuit 2, i = current in circuit 2, Z = circuit 2 impedance, and ω = angular velocity ($2\pi f$). M is not constant but increases with frequency.

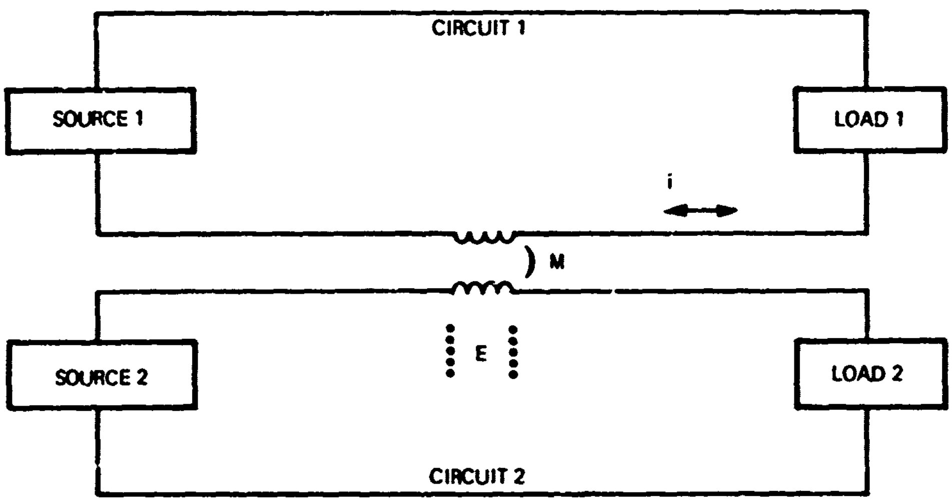


FIGURE 6-7 MUTUAL INDUCTANCE COUPLING

SUSCEPTIBILITY TO EMI

Any equipment or components designed to respond to electrical energy will be susceptible to EMI to some degree. If the interference level is of sufficient amplitude to produce a response, then the EMI must be considered in terms of performance degradation. Equipments such as communications and radar receivers are common to many applications and frequently present susceptibility problems because they respond to relatively low-level signals. Obviously these equipments must be considered in evaluating system compatibility. However. other equipments or devices that respond to electrical or magnetic energy should not be ignored. Examples of other devices that must be considered include control equipment, computers, telemetry equipment, amplifiers, test instrumentation, output devices or indicators, and electroexplosive devices.

Three basic categories of interference effects should be considered. Assignments of criticality categories are based on the impact of electromagnetic interference or susceptibility on the performance of assigned missions. The categories according to MIL-E-6051D are:

Category I: EMC problems that could result in loss of life, loss of vehicle, mission abort, costly delays in launches, or unacceptable reduction in systems effectiveness.

Category II: EMC problems that could result in injury, damage to the vehicle, or reduction in systems effectiveness that would endanger the success of mission.

Category III: EMC problems that result only in annoyance, minor discomfort, or loss of performance that does not reduce desired system effectiveness.

RECEIVING SYSTEMS

For EMI to affect a receiver, the interference must either contain frequencies within the range being processed by the receiver, or it must be capable of degrading the normal processes of the receiver. The band of frequencies over which the receiver can respond to EMI is much wider than that normally considered to be the receiver bandwidth. Attenuation of frequencies outside the receiver normal bandwidth is never sufficient to produce total rejection of large interfering signals even though their frequencies may be considerably removed from those the receiver is designed to accept.

In addition to placing energy in the receiver passband, there are other means whereby EMI can cause receiver interference. Receiver overload is the result of excessive signal amplitude in any stage. If sufficiently strong EMI on any frequency causes an amplifier stage to operate in the nonlinear portion of its transfer characteristic, that stage will act as a mixer/demodulator. An overloaded stage acting as a mixer/demodulator can produce any of several effects:

1. Amplifier nonlinearity will limit amplitude and desensitize the receiver to the desired signal. This effect can occur even without the interfering signal being processed through the receiver to the output terminals.

2. Radio frequency EMI reaching an overloaded audio or video amplifier, perhaps through a control, power, or output cable, will be demodulated and produce interference in the receiver output.

3. Radio frequency EMI reaching any overloaded stage or normal mixer/demodulator along with the desired signal can produce cross-modulation of the desired signal.

4. Two radio frequency EMI signals can intermodulate with each other in any overloaded stage or normal mixer, and if a beat product falls within the receiver tuned frequency passband of the IF amplifier passband, interference will appear at the receiver output.

5. Harmonics produced by nonlinearities in the first stage, or by protective limiters ahead of the first stage, can be coupled into the antenna and radiated to cause interference in other equipments.

Receiver spurious responses not the result of overload can occur on certain specific frequencies to which the receiver is susceptible because of frequency conversion. These responses include:

1. Image responses produced by the falling of unwanted signals, including noise, on a frequency that differs from the local oscillator frequency by the amount of the intermediate frequency, but on the opposite side of the local oscillator from the wanted signal.

2. Local oscillator harmonics beating with undesired signals to produce a product that falls within the IF bandpass.

3. IF feedthrough that is the result of unwanted signals on an intermediate frequency reaching the IF amplifier, either through the normal amplifier chain or through the wiring of the receiver.

Communication Receivers

Interference effects in communication receivers can appear as background noise, signal distortion, or static in the communication headset or as message errors in a data processing device. Although low-level interference may not render communication receivers inoperative, it irritates and tires an operator. As the interference level is increased, the effects become more severe, and the communication receiver may be unable to perform the primary function for which it was intended. For example, high-level EMI may mask or override the desired signal, produce serious distortion or message errors, generate a spurious response, or desensitize the receiver to the desired signal.

Detection, Tracking, and Navigation Radars

EMI can produce a variety of effects on radar and navigation equipments. One relatively common form of interference to radar receivers is pulse interference from other radars. In search radars, the effects of pulse interference appear as dots or spirals on the radar scope presentation, usually moving continuously, and may cover large portions of the scope face. This makes targets difficult to detect and increases operator fatigue. If the interference occurs in the target sector, delayed detection or false alarms can result. In tracking radars,

pulse interference presents serious problems during the target acquisition phase because strong interfering pulses can produce target-like signals that impair acquisition of the desired target.

Although CW interference in radar receivers is not as obvious as pulse interference, it can produce serious problems. One serious effect of CW interference to radar receivers is desensitization. In addition to being desensitized, a pulse radar operating near a powerful CW transmitter can be made completely inoperative if the CW level is sufficient to fire the transmit-receive duplexer continuously. In fact, once the transmit-receive tube has been fired by its own transmitter, lower levels of CW may be sufficient to maintain ionization in the tube and thereby make the radar inoperative. Certain transmit-receive tubes have been found to remain in conduction for CW power levels as low as 20 milliwatts.

Electronic Countermeasures Receivers

Many combat aircraft are equipped with electronic countermeasure (ECM) receivers to locate signal-emitting targets or to warn the pilot that the aircraft is being observed or tracked by radar. ECM receivers fall into two general categories: "wide open" receivers using a crystal detector followed by a video amplifier, and tunable selective receivers with a relatively wide tuning range. Either type may initiate certain actions automatically. For example, an ECM receiver may operate in the search mode until it detects a signal that matches previously programmed characteristics, then activate a jammer or spoofer.

EMI can affect ECM receivers in a variety of ways, depending upon the function and characteristics of the receiver. The wide open type has little or no frequency discrimination, so almost any EMI frequency can enter unattenuated. Such a receiver may serve as a tail-warning system, or several may be combined in an azimuth-indicating system. EMI can produce false alarms and false azimuth indications. The tunable type usually has sufficient frequency-scanning range that receiver spurious responses are a problem. Both types are likely to be so highly susceptible to on-board radars that it is necessary to blank the ECM receiver while the radar pulse is being emitted.

Jammer or spoofer transmitters, when an aircraft is so equipped, constitute a compatibility problem of the greatest magnitude. Most jammers are designed for continuous emission of wide-band noise of relatively high power, which can affect not only the ECM receivers but all other avionic systems as well. Spoofers are similar to transponders in that they intercept radar pulses, hostile in this case, and reply with simulated target pulses. The transmitted pulse is usually a wideband noise burst, to which deceptive information regarding target size, range, azimuth, or rate is applied. Figure 6-8 is a simplified block diagram of an ECM system.

The receiver portion that controls the jammer or spoofer must be sufficiently free of EMI to locate its intended victim and to program its ECM action. The transmitter portion must be sufficiently isolated from other components, including its associated receiver, so that its transmitted energy does

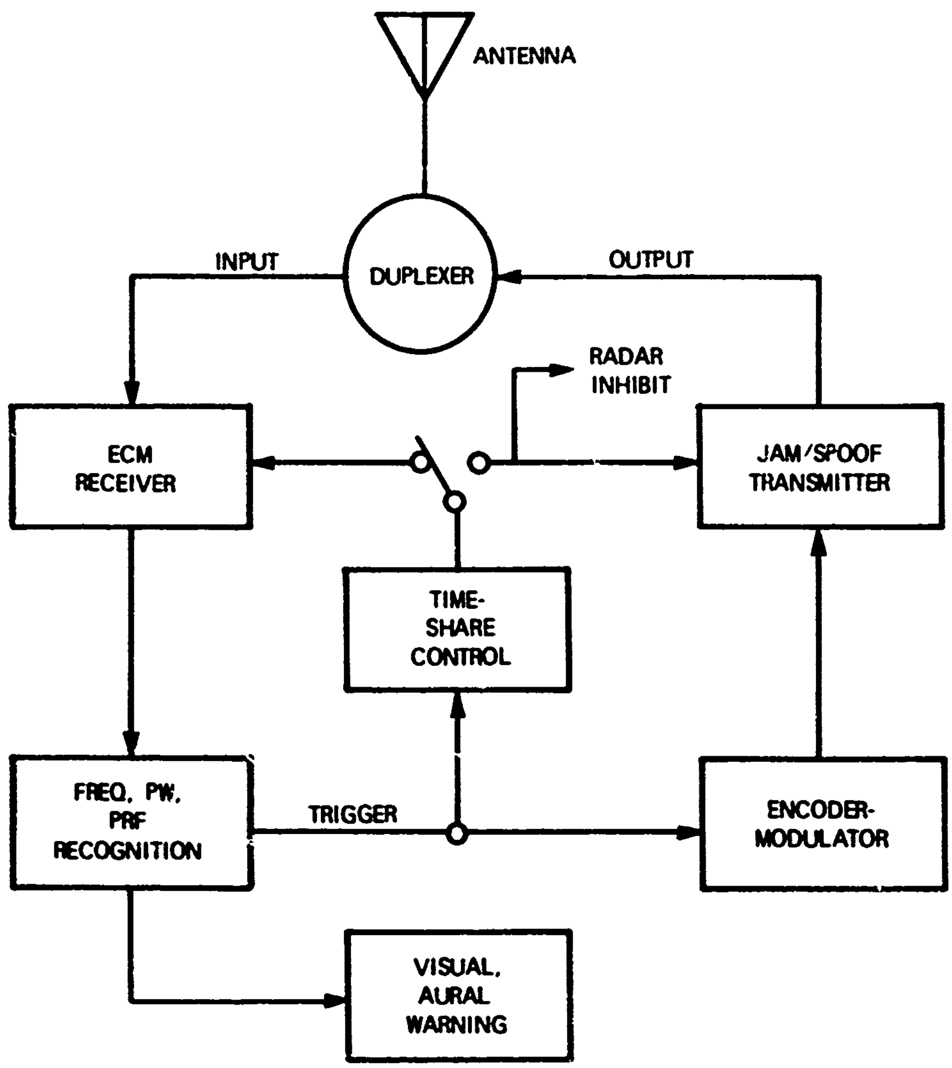


FIGURE 6-8 SIMPLIFIED ECM SYSTEM BLOCK DIAGRAM

not degrade their performance. The usual remedy is to operate the jammer or spoofer on a time-shared basis to give the radars and ECM receivers a quiet period of a few milliseconds in which to update their information. However, this reduces the effectiveness of the jammer because it also gives the hostile system being jammed an opportunity to update its information. Additional EMI-reduction measures include isolation between transmitting and receiving antennas, isolation between control, signal and power cables, and shielding and bonding.

Radio Aids to Navigation

Aircraft are equipped with various radio aids to navigation, depending upon their type and mission. Because aircraft must sometimes be operated solely by reference to instruments, safety of flight can depend upon freedom from perturbations in the devices that supply the aircraft with navigation reference points. Typical radio aids to navigation, and their susceptibility problems are discussed below but the list is by no means a complete one.

The automatic direction finder (ADF) is a receiver equipped with a direction-sensing antenna. Its function is to provide relative bearings on fixed ground reference transmitters. In the presence of noise, particularly thunderstorms, the directional indication may swing wildly. Bearing errors may also be produced by reflections from radio and TV towers or from mountains.

Tactical air navigation (TACAN) and VHF omni-range (VOR) both provide means for an aircraft to determine its magnetic azimuth from a surface transmitter. VOR operates in the VHF range and TACAN operates in the SHF band, but the two systems are electronically similar. The receiving equipment in the aircraft senses the phase difference between two modulation components of the received signal–one generated by electronic modulation of the reference signal and the other a physical modulation produced by rotation of the transmitting antenna structure. Accuracy depends upon the ability of the aircraft receiver to sense phase angle information. Deleterious EMI may come from radar pulses (including IFF and DME) as well as noise and the other usual receiver difficulties. Shipboard TACAN antennas frequently are victims of lightning damage that can degrade the azimuth data without the ship realizing it.

The instrument landing system (ILS) is a runway approach radio aid in the VHF band. It is related to VOR and they may share the same receiver and instrument panel indicator. ILS consists of a pair of runway localizer beams that provides a heading to (and from) the instrument runway, and a pair of glide-slope beams that provide vertical descent information. Heading and glide-slope information is obtained in the aircraft by sensing the relative amplitudes of pairs of modulated beams. The aircraft receivers are subject to the usual EMI problems of noise, image responses, overload, and cross-modulation by nearby systems. The shape of the beams, and consequently the indicated flight path, are also affected by the reflectivity of the ground and objects on the ground such as other aircraft and hangars.

Identification, friend or foe with selective identification feature (IFF/SIF), and distance measurement equipment (DME) are both beacon transponder aids

to navigation operating in the L-band. IFF/SIF is used in conjunction with surveillance radars to provide positive identification of aircraft and to increase tracking ranges, with the transponder located in the aircraft. DME places the transponder on the surface (at the TACAN transmitter) and the interrogator-responsor in the aircraft. Both systems use pulse-position coded interrogation and reply. Because the two systems use comparable frequencies, they are subject to mutual interference, as well as to interference from L-band radars. Strong noise can also cause false triggering of the transponders, or, for DME, erroneous readouts and loss of lock of the range indicators.

Underwater Detection and Classification

ASW aircraft can be equipped with a variety of electromagnetic devices for detecting, identifying, and tracking underwater targets. The principal ASW sensors are magnetic anomaly detection (MAD) systems, sonobuoy systems, and for ASW helicopters, dipping sonar.

The MAD system detects perturbations in geomagnetic lines of force produced by the presence of objects having greater permeance than their surroundings. The sensor device is highly susceptible to magnetic influences in the aircraft, even those caused by changes in the aircraft attitude and current surges on the aircraft power distribution system.

The sonobuoy system consists of acoustic transducers suspended from small buoys containing transmitters that telemeter underwater sounds back to a detection and tracking device in the aircraft. The position of the target is determined by comparing the relative acoustic levels in pairs of sonobuoys. Because submarine sounds are likely to be masked appreciably by incidental water noise, further degradation by comparatively small amounts of EMI at the receiver site in the aircraft can cause loss of target detection, identification, and tracking capability.

The dipping sonar system is used by ASW helicopters while in a hover position. It consists of an echo-ranging ultrasonic transducer suspended from the helicopter, with electrical cables connecting the underwater transducer to the transmitter and receiver in the helicopter. Operation of the hoist and train drive motors and keying of the transmitter can cause EMI to other systems in the helicopter. The sonar receiver and display are susceptible to the EMI effects previously discussed for receiving systems in general.

UNINTENTIONAL RECEIVERS

Many devices not intended to act as receivers are nevertheless susceptible to EMI. The folklore of radio abounds with stories of radio reception by teeth fillings, bedsprings, telephones, and kitchen sinks. Many devices not commonly considered to be electrical, as well as almost any electrical device, are susceptible to EMI from extraneous sources. An aircraft contains many such devices: panel instruments, servo amplifiers, and intercom systems.

Flight Control, Instrumentation, and Display

Aircraft have numerous control, measurement, and display functions that are performed electrically. Although these flight controls and instruments are not intended to function as radio receivers, they often are susceptibile to on-board interference from electrical and magnetic fields. The effect of EMI is a false indication on the instrument read-out or an error in flight path or maneuver. Many of these devices are associated with intentional radio receivers that are also susceptible: for example, TACAN, VOR, ILS, and radar.

The complexity of the flight control and instrumentation system will vary radically depending upon the type of craft, but even a simple magnetic compass can be affected by EMI involving magnetic fields. Other flight control and instrumentation devices susceptible to EMI include:

Fluxgate compasses
Autopilots and attitude stabilizers
Electronic ATTACK/NAV computers
Electronic computing gunsights/bombsights
Inertial and satellite navigation systems
Radar altimeters
Terrain clearance radars
Doppler drift radars
TACAN/DME indicators
VOR/ILS indicators
Electrically-actuated engine and fuel gauges
Electrically-actuated telemetry sensors
Electrically-actuated pressure altitude and speed indicators

Because these devices respond to electrical or magnetic energy, an interfering signal can generate erroneous readings in the device. This might result in a faulty control function, the loss of vital information, or it could cause an aircraft or missile to go off course. This can be a very serious type of interference because the malfunction of a control device can result in the loss of the aircraft or missile.

Servo Systems and Control Actuators

The control surfaces of modern jet aircraft have such great aerodynamic forces operating on them that it is difficult for the pilot to position them manually. Even smaller and slower aircraft use autopilots and flight stabilizers to assist the pilot. Most pilot-assist systems use electronic servo amplifiers and electromechanical power transducers.

The servo amplifier accepts electrical inputs (from the autopilot, for example), modifies them as required by the function being controlled, and delivers electrical power to operate an electromechanical actuator device. The servo amplifier unit normally contains modulators, demodulators, amplifiers, limiters, summing networks, phase shift networks, feedback networks, and switches. The servo amplifier exhibits high gain to low level signals and depends

upon degenerative feedback networks and amplitude limiters to hold its working gain to reasonable levels. EMI that enters the servo amplifier at other than the normal input terminals is likely to be operated upon regeneratively rather than degeneratively by the feedback networks.

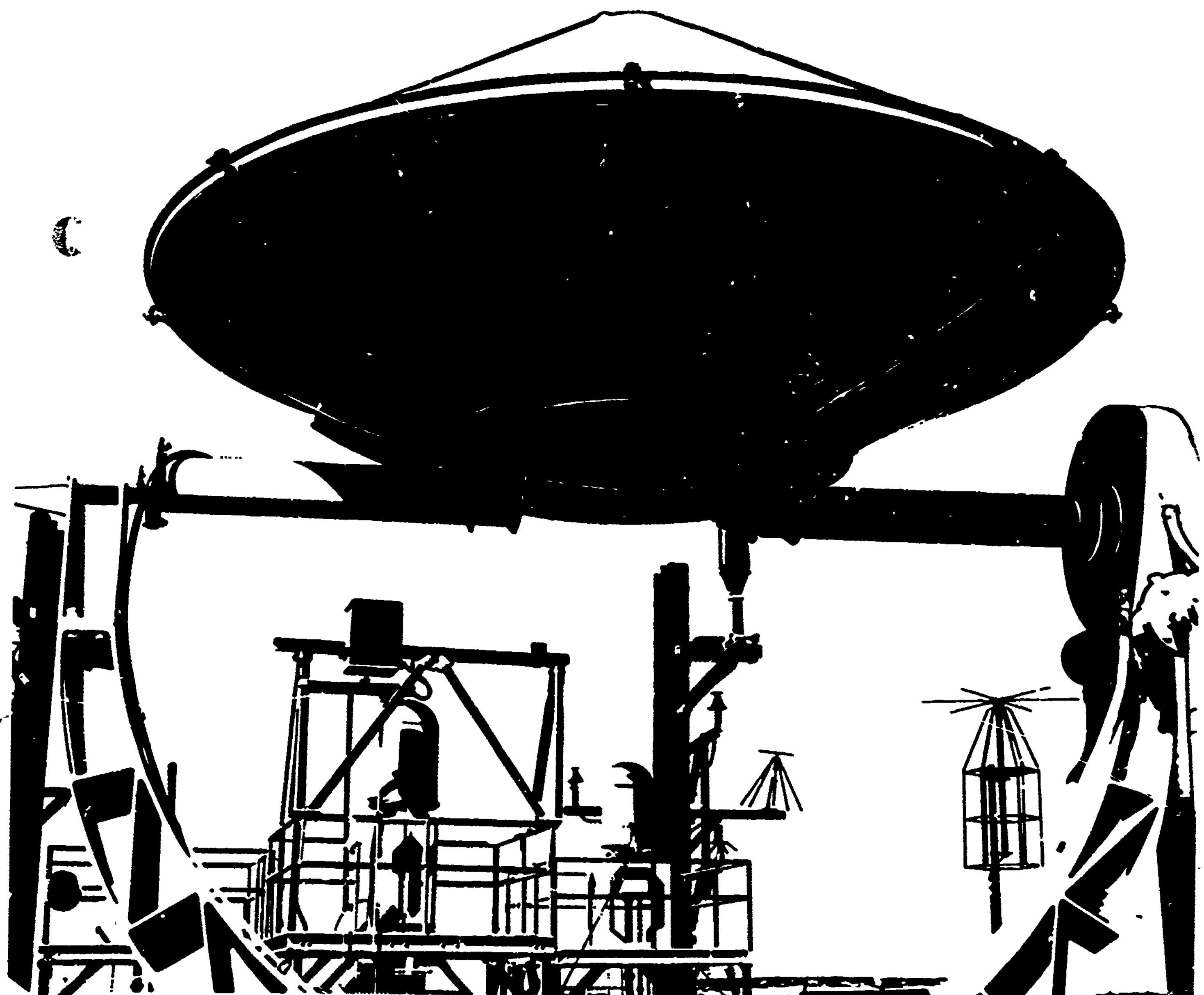
The control actuator may be an electrical motor or an electrohydraulic valve that operates to position a mechanical load. Rate feedback and position feedback are used to stabilize the control loop. The presence of EMI in the control actuator, especially in the rate or position feedback sensors, can cause erroneous positioning of the load or oscillation ranging from slight to destructively severe.

NAVAIR 5335

NAVAL AIR SYSTEMS COMMAND

ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 7



PUBLISHED BY DIRECTION OF COMMANDER, NAVAL AIR SYSTEMS COMMAND

CHAPTER 7
MILITARY EMC STANDARDS AND SPECIFICATIONS

CONTENTS

TABLES

INTRODUCTION AND HISTORY

A standard is created primarily to serve the designer and to control variety. It may concern materials, items, features, engineering practices, processes, codes, symbols, type designations, definitions, test, inspection, packaging and preservation methods and materials, definition and classification of defects, and standardization of marking materials, items, parts, and components. In drafting the equipment specification, a standard is very useful because it can establish common parameters of interchangeability, compatibility, reliability, and maintainability. A standard can provide the designer with a uniform description for the identification of selection and application data. The control of variety does not necessarily follow automatically, however, therefore common features must be specified, usually by standards.

A specification is intended primarily for use in procurement. It defines clearly and accurately essential technical requirements usually expressed in terms of performance and provides the instrument for solicitation of competitive bids from the largest possible segment of industry. This leads to lowest cost procurement for the Government.

Military EMC specifications and standards have as their objective minimizing the effects of EMI, which can be encountered through use of electromechanical electrical and electronic equipments, subsystems, and systems. The U. S. Government and industrial activities have had the problem of operating and maintaining potentially susceptible communications, navigation, surveillance, control, measurement, and data handling subsystems in complex electromagnetic environments. This has resulted in extensive effort to design and fabricate electronic systems, subsystems, and equipments that will perform effectively in the anticipated electromagnetic environment.

The Federal Communications Commission has also been active in EMI control. Many potential and actual problems have been reviewed and controlled. The FCC also has specified radiation limits and frequencies for unintentional sources of RF energy such as diathermy machines and plastic-forming heaters, and has also set limits on the allowable radiation from receiver local oscillators.

There is a need for continuous standardization for electromagnetic compatibility to avoid conflicting and overlapping requirements that can result in non-uniform and costly engineering, production, test, and installation. The control of electromagnetic compatibility has, to a large degree, been attempted through suppression after the engineering design stage. This increases the development and procurement costs and usually results in relatively unsatisfactory and unreliable operation. Standardization, evaluation, and application of control measures in the original design, rather than remedial measures, will greatly reduce operational EMI problems. Compatibility can be achieved through development, coordination, and implementation of EMC design criteria and evaluation procedures.

Over the last two decades, the electromagnetic compatibility field has grown from near infancy to a complex giant. This growth has been accompanied by consolidation and updating of standards and specifications that cover electromagnetic emission and susceptibility characteristics, measurements, and requirements for equipments, subsystems, and systems. In the past, the Army, Navy, and Air Force have used standards and specifications that had similar objectives but that had variations in test requirements, test techniques, and scope.

One of the earliest electromagnetic interference specifications was the joint Army/Navy specification JAN-I-225 of June 1945. This specification contained test procedures to be used in conjunction with specification AN-I-27. The latter document was established to control interference in aircraft electrical systems. AN-I-27 was superseded by AN-I-42, which was in turn superseded in June 1950, by MIL-I-6181. This latter specification contained specific interference requirements for the measurements required by JAN-I-225. The above specifications were to be applied only to aeronautical voice communication equipment of the Army, Air Force, and Navy.

The changes listed below in the titles of successive versions of specification MIL-I-6051 (known later as MIL-E-6051) give a broad view of changes in the electromagnetic compatibility field.

MIL-I-6051 dated 28 March 1950, titled, *"Interference Limits and Methods of Measurement, Aircraft Radio and Electronic Installations."*

MIL-I-6051A (USAF), 23 January 1953, titled, *"Interference Limits and Methods of Measurements, Electrical and Electronic Installations in Airborne Weapons Systems and Associated Equipment."*

MIL-E-6051C, 17 June 1960, titled, *"Electrical-Electronic System Compatibility and Interference Control Requirements for Aeronautical Weapon Systems, Associated Subsystems and Aircraft."*

MIL-E-6051D, 7 September 1967, titled, *"Electromagnetic Compatibility Requirements, Systems."*

The situation grew progressively more complicated and between 1950 and 1967 at least eighteen different single-service or coordinated standards and specifications (and amendments to them) were developed. These documents are listed below.

Number	Date	Number	Date
MIL-I-6181	June 1950	NAVFAC 50-Y	April 1966
MIL-S-10379	July 1950	MIL-STD-449	May 1960
MIL-I-11683	Jan. 1952	MIL-E-6051	June 1960
MIL-STD-220	June 1952	MIL-STD-826	Jan. 1964
MIL-I-17623	Sept. 1953	MIL-I-43121	April 1964
MIL-S-13237	Jan. 1954	MIL-E-55301	April 1965
MIL-B-5087	July 1954	MIL-S-12348	Nov. 1955
MIL-I-16910	August 1954	MIL-I-11748	May 1956
MIL-I-26600	June 1958	MIL-STD-1310	April 1967

STANDARDIZATION EFFORT

By authority of a directive from the Deputy Secretary of Defense, dated 27 November 1963, a combined working group of Department of Defense and industry personnel was established to determine means of improving procurement practices through better management of DoD specifications and standards. The working group uncovered several areas where a concentrated effort was needed. One of the areas was electromagnetic interference. The Defense Industry Advisory Council working group found the basic deficiency to be conflicting and overlapping requirements in interference control specifications and standards, thereby resulting in non-uniform and costly test and control practices. They recommended that the appropriate military department take the necessary action to reduce the areas of conflict.

Therefore, in January 1965, the Office of the Assistant Secretary of Defense for Installations and Logistics, in coordination with ODDR&E, initiated a program through the Standardization and Engineering elements of the Commanding General, Army Electronics Command, the Chief of Naval Material, and Air Force Deputy Chief of Staff, Systems, and Logistics to:

a. Standardize interference control requirements and measuring techniques appearing in numerous documents, (coordinated and single-service)
b. Reduce the number of documents and requirements to a minimum
c. Simplify requirements
d. Eliminate marginal requirements

In March 1965 a meeting of engineering and standardization personnel

from each service was held to establish officially a program to develop standards in:

a. EMI terminology
b. EMI test methods
c. EMI requirements for equipment

The Navy's Bureau of Ships (now Naval Ship Systems Command) was designated the preparing activity for study drafts on the above areas. The Army Electronics Command and the Air Force Systems Command were designated departmental custodians. OASD (I&L) reserved the MIL-STD-460 through MIL-STD-469 numbers for EMC standards developed during this and future standardization projects.

MIL-STD-461, 462, and 463

The initial study progressed to the point where specific areas were identified and documents were under preparation by a working group. To expedite completion of the documents, the following projects were initiated in July 1965:

Project Number	Description	Preparing Activity	Custodians
MISC-0349	Definitions and Systems Units, Electromagnetic Interference Terminology, (MIL-STD-463)	Army (EL)	Navy (SH) and AF (11)
MISC-0350	Electromagnetic Interference Characteristics Requirements for Equipment, (MIL-STD-461)	Navy (SH)	Army (EL) and AF (11)
MISC-0351	Electromagnetic Interference Characteristics, Measurement of, (MIL-STD-462)	AF (11)	Army (EL) and Navy (SH)

Drafts of the above standards were distributed throughout the military and industry for final coordination. The documents were officially issued on the following dates.

Standard	Effective Date
MIL-STD-461	31 July 1967
MIL-STD-462	31 July 1967
MIL-STD-463	9 June 1966

As a result of this standardization effort, ten of sixteen documents listed under "Introduction and History," were superseded. However, these ten documents

may still be cited in the reprocurement of equipments designed to the superseded documents.

MIL-STD-469

Concurrent with the Development of MIL-STD-461, 462, and 463, OASD (I&L), in coordination with ODDR&E, initiated another project in April 1966, to develop and coordinate a radar design standard based on the Interdepartment Radio Advisory Committee (IRAC) notice of 1 August 1962, "Radar Engineering Design Objectives (REDO)." The Navy Ship Systems Command was again designated preparing activity with the Army Electronics Command and the Rome Air Development Center of Air Force Systems Command, the departmental custodians. The assignment was completed with the issuance of MIL-STD-469, Radar Engineering Design Standard, dated 1 December 1966.

LATER STANDARDIZATION PROJECTS

During the MIL-STD-461, 462, 463 coordination effort, it became apparent that there remained many areas requiring additional study and documentation. Consequently, it was recommended to OASD (I&L) that consideration be given to establishing the following projects:

a. Update MIL-STD-463 by an amendment
b. A revision to MIL-STD-461 and 462 in the following areas:
    1. Updating test methods and limits
    2. Correlating emission and susceptibility limits of communication-electronic (C-E) equipment
    3. Developing minimum criteria for EMC test equipment to assure that the equipments can measure to the prescribed requirements of MIL-STD-461 and 462
c. A standard detailing EMC requirements for systems. This project would result in an expansion of a limited coordination systems standard, MIL-E-6051, for use in all systems
d. A standard detailing bonding and grounding requirements for EMC control. This project would consolidate two existing standards, MIL-STD-1310 (SHIPS) and MIL-B-5087
e. An EMC design handbook to detail design techniques reduces the probability of troublesome interference. This project would consolidate approximately 4,000 sources of design information
f. An overall EMC Program Requirements Standard to combine all aspects of EMC requirements and techniques, and their relationships with similar documents
g. A revision and expansion of MIL-STD-469 to include design requirements for other types of electronic equipment such as sonar, telemetry, ECM, and communications

As a result of the above recommendations, the following projects were initiated:

Project No.	Description	Preparing Activity
58GP-0002	Revision of MIL-STD-469	Navy (SH)
MISC-0442	EMC design handbook	Army (EL)
MISC-0443	EMC bonding/grounding requirements	Navy (SH)
MISC-0462	EMI/EMC program standard	Navy (SH)
MISC-0488	Revision of MIL-STD-463	Army (EL)
MISC-0463	EMC requirements for systems	AF (11)

Explanation:

Navy (EC) - Naval Electronic Systems Command
Navy (SH) - Naval Ship Systems Command
Army (EL) - Army Electronics Command
AF (11) - Aeronautical Systems Division, AF Systems Command
AF (17) - Rome Air Development Center, AF Systems Command

Revision projects for MIL-STD-461 and 462 have since been established.

In addition to the above projects, revision of MIL-STD-449, Radio Frequency Spectrum Characteristics, Measurement of, was recommended by the working group that developed the standard. The document contains test methods for measuring spectral characteristics required for electromagnetic compatibility studies performed by ECAC and for applications for frequency assignments. Because several procedures in MIL-STD-449 measure parameters required by MIL-STD-461, 462, and 469, it was also recommended that revisions of these standards eliminate the discrepancies and duplications.

DoD ELECTROMAGNETIC COMPATIBILITY STANDARDIZATION PROGRAM (EMCS)

The DoD Directive 3222.3 of 5 July 1967 established the DoD Electromagnetic Compatibility Program (EMCP) and placed the responsibility for standardization with the Secretary of the Navy or his designee. The Office of Technical Data, Standardization Policy and Quality Assurance within OASD (I&L) designated the Naval Electronics Systems Command as the Area Assignee Activity for EMC in its memorandum of 31 August 1967. The memorandum also defined the scope of the task to cover "...a complete range of component, circuit, equipment, subsystems, and system electromagnetic compatibility. Related standards for prediction, measurement, and validation for EMC are also to be included."

Participating activities designated for the program are now:

a. Army Electronics Command
AMSEL-TD-SS
Ft. Monmouth, New Jersey 07703

b. Engineering Standards Division (SCS-23)
Headquarters Air Force Systems Command (10)
Andrews Air Force Base
Washington, D. C. 20331

c. Naval Electronic Systems Command, ELEX 0517,
Washington, D. C. 20360

In addition to the above, the National Security Agency (NSA) and National Aeronautics and Space Administration (NASA) were requested to participate in the development and coordination of the EMCS. NSA has established a Program Management Office for EMC at Fort Meade, Maryland, and will coordinate all documents related to EMC standardization. NASA is also currently participating in the program. Recently several other agencies requested participation in the program. Accordingly, the Defense Communications Agency (DCA), Electromagnetic Compatibility Analysis Center (ECAC), and the Federal Aviation Administration (FAA) have been added as participating activities. Industry participates in the program through various groups such as Electronic Industries Association, Aerospace Industries Association, Institute of Electrical and Electronics Engineers, and the Society of Automotive Engineers.

STATUS OF EMC STANDARDIZATION PROGRAM

The present EMCS program includes eight joint-service standards and specifications, which are listed below. Because they are undergoing a continuing review and revision, the suffix letter is subject to change.

Number	Title	Preparing Activity
MIL-STD-220	Method of Insertion Loss Measurement	Army (EL)
MIL-STD-449D	Radio Frequency Spectrum Characteristics, Measurement of	Navy (EC)
MIL-STD-461A	EMI Characteristics Requirements for Equipment	Navy (EC)
MIL-STD-462	EMI Characteristics, Measurement of	Air Force (11)
MIL-STD-463	Definitions and System of Units, EMI Technology	Army (EL)
MIL-STD-469	Radar Engineering Design Requirements, EMC	Navy (SH)
MIL-B-5087	Bonding, Electrical, and Lightning Protection for Aerospace Systems	Air Force (11)
MIL-E-6051D	EMC Requirements for Systems	Air Force (11)

A ninth joint-service EMCS program document has been approved for inclusion following revision:

Number	Title	Preparing Activity
MIL-STD-285	Attenuation Measurements for Enclosures, Electromagnetic Shielding for Electronic Test Purposes, Measurement of	Army (EL)

The single-service document below is currently in effect, but the EMCS program proposes to consolidate it, MIL-B-5087, and other bonding/grounding documents into a single standard.

Number	Title	Preparing Activity
MIL-STD-1310 (SH)	Shipboard Bonding and Grounding Methods for EMC	Navy

Thirteen superseded documents listed below are being monitored under the EMCS program:

MIL-S-10379	July 1950	MIL-STD-826	January 1964
MIL-I-11683	January 1952	MIL-I-43121	April 1964
MIL-I-17623	September 1953	MIL-E-55301	April 1965
MIL-S-13237	January 1954	MIL-S-12348	November 1955
MIL-I-6181	November 1959	MIL-I-11748	May 1956
MIL-I-26600	June 1958	NAVFAC 50-Y	April 1966
MIL-I-16910	October 1964		

CURRENT AND FUTURE REQUIREMENTS

CURRENT REQUIREMENTS

Electronic devices upon which the armed forces depend, are influenced by electrical or magnetic fields in the environment in which they operate. The environment is commonly contaminated by a multitude of incidental and spurious emissions from various transmitting, receiving, control, and data processing equipments that are used in sophisticated military operations, as well as by other sources. These radiated and conducted emissions may impair system operation by producing perturbations in sensitive electronic circuits of the system.

EMC requirements, which are directed at planning a system so that all elements function in harmony with each other and with other systems, are being approached in two ways. The first is to control all emissions so that those not necessary to the mission are suppressed; the second is to reduce the susceptibility of sensitive equipments to extraneous emissions. Much effort has gone into the development of informative documents that will assure systems effectiveness in terms of electromagnetic compatibility.

The EMC documents that have been developed are now being used, and compliance with them is being required on all new designs and procurements of electrical, electromechanical, and electronic systems, subsystems, and equipment. Implementation of these documents will not improve existing electromagnetic environments, but should prevent further degradation of the environment and provide for optimum use of the electromagnetic spectrum. As older systems, subsystems, and equipment are gradually retired from service, the situation should improve appreciably.

FUTURE REQUIREMENTS

The future will bring greater sophistication of electronic systems in virtually every field. Micro-electronics will allow more sophisticated systems for fixed installations, and for mobile installations such as aircraft, ships, submarines, motorized vehicles, missiles, and space vehicles. In addition to the increasing complexity of systems, a greater number of systems will be in operation. This general expansion of electronics will create additional congestion in the electromagnetic spectrum and thereby increase the likelihood of interference between systems, subsystems, and equipment. Hence each electronic device will be required to emit and receive only those signals that are needed to perform its mission.

To increase the probability of mission success in this congested environment, all electrical, electromechanical, and electronic systems, subsystems, and equipments will be required to meet rigid electromagnetic compatibility requirements. This is being accomplished now to some degree through implementation of the latest military specifications and standards. The specifications and standards, as they now exist, will probably not be adequate for systems of the future, but they provide a valuable step in the proper direction. Present efforts among the authors of specifications and standards are turning away from the time-proven but outdated two-dimensional characteristics such as amplitude vs. time, frequency vs. time, and amplitude vs. frequency, in favor of transient testing. Transient testing requires simultaneous recording of time, frequency, and amplitude to yield definitive data. Transient testing techniques are relatively more difficult, require more elaborate test equipment, are more difficult for technicians to understand and to interpret. The two-dimensional techniques are easily instrumented and produce reliable results. Two-dimensional techniques have the disadvantage of requiring more testing time and additional data processing. These two techniques will coexist in future standards and specifications if a true interest is taken in costs and results. It is

anticipated that there will be a realization that both methods have merits and should be used selectively.

Careful documentation of new compatibility problems will aid in keeping standard requirements current. The vast amounts of measured data currently being collected in the form of spectral characteristics and environments under the Department of Defense Electromagnetic Compatibility Program will also provide much of the insight needed for continuing adequacy of these levels.

For some time, there has been a push in the EMC testing to automate some of the measurements. Sweep frequency sources and digital controllers are currently being used with recording devices to provide a degree of semi-automated testing.

EMC SPECIFICATIONS AND STANDARDS AND RELATED DOCUMENTS

DESCRIPTION AND APPLICATION

Current EMC and related specifications and standards are listed in Table 7-1. These documents represent a technical and managerial effort expended over many years. Efforts are continuing on revisions and development to improve existing documents, and to reflect continuing advancement in electric and electronic systems, subsystems, and equipments to be used by the Armed Forces. Some of these documents give actual limits for both susceptibility and emission tests on equipments, subsystems, and systems under procurement. Ideally, if several pieces of equipment comply with applicable emission and susceptibility requirements, they will be compatible when incorporated into a system. Unfortunately, this may not always be true. The requirements specified may be too severe in some situations and too liberal in others, so it is frequently necessary to modify certain general standards to suit a particular system, environment, or installation.

All EMI problems cannot be solved by application of highly developed EMI specifications and standards, but they can be reduced.

GENERAL AND SPECIFIC REQUIREMENTS

MIL-STD-461A

This standard is entitled "Electromagnetic Interference Characteristic Requirements for Equipment," and is a multi-service coordinated standard covering the requirements and test limits for measurement and determination of electromagnetic emission and susceptibility characteristics of electronic, electrical, and electromechanical equipment. It references MIL-STD-462 for test procedures and MIL-STD-463 for definitions and systems of units. The requirements apply to general or multi-service procurements and single service procurements, as specified in the individual equipment specification of the

contract or order.

The requirements specified therein are established to:

a. Insure that interference control is considered and incorporated into the design of equipment
b. Enable compatible operation of the equipment in a complex electromagnetic environment

The following standards and specifications were superseded by MIL-STD-461:

Coordinated Documents

MIL-I-6181
MIL-S-10379
MIL-S-12348
MIL-I-43121

Table 7-1 Current EMC and Related Specifications and Standards

Specification Number	Title
MIL-STD-220	Method of Insertion Loss Measurement
MIL-STD-449	Radio Frequency Spectrum Characteristics, measurement of
MIL-STD-461	EMI Characteristics Requirements for Equipment
MIL-STD-462	EMI Characteristics, Measurement of
MIL-STD-463	Definitions and System of Units, EMI Technology
MIL-STD-469	Radar Engineering Design Requirements, EMC
MIL-STD-1310 (Ships)	Shipboard Bonding/Grounding Methods for EMC
MIL-B-5087	Bonding, Electrical, and Lightning Protection for Aerospace Systems
MIL-F-15733	Filters, Radio Interference, Requirements for
MIL-E-6051	Electromagnetic Compatibility Requirements, Systems
MIL-STD-285	Attenuation Measurements for Enclosures, Electromagnetic Shielding for Electronic Test Purposes, Measurement of

Single Service Documents

Army	Navy	Air Force
MIL-E-55301	MIL-I-16910	MIL-STD-826
	MIL-I-17623	MIL-I-26600
	NFEC-Spec-50Y	

The requirements contained in three specific documents, which may be called for by contract, are set forth in MIL-STD-461A. The documents are:

a. Interference Control Plan
b. EMI/EMC Test Plan
c. Test Report

The interference control plan outlines in detail the interference control or reduction program, the engineering design procedures, and proposed techniques that will be used to determine conformance with the requirements of MIL-STD-461A and that will enable the equipment to perform its operational function without interference from its parts and subassemblies. The control plan contains a discussion of the following major categories: Management Controls, Frequency Management, EMI Mechanical Design, Electrical/Electronic Wiring and Circuit Design, Prediction of Analysis Techniques, and the R&D Testing Program proposed during development construction stages. The control plan must be approved by the procuring activity before it can be officially implemented.

The EMI/EMC Test Plan details ways to conduct and apply test procedures to verify compliance with the applicable EMI/EMC requirements of MIL-STD-461A. Approval of the test plan precedes formal testing.

The following types of tests are covered by MIL-STD-461A:

a. Emission Tests (CE and RE) - The levels of emissions from the equipment under test are measured and compared to a limit, above which unacceptable emission levels occur
b. Susceptibility Tests (CS and RS) - Prescribed levels of conducted or radiated emissions are applied to the equipment under test to see if it malfunctions or is susceptible to these emissions

In determining requirements for any specification, it is of primary importance to include appropriate EMI limits over the necessary frequency range. MIL-STD-461A gives interference limits and susceptibility limits in the frequency range from 30 Hz to 40 GHz. Some of the limits are in graphical form for the narrowband and broadband measurements. The suitability of measuring equipment depends upon sensitivity, bandwidth, and other characteristics.

MIL-STD-461A classifies electronic, electrical, and electromechanical equipment into four general classes as shown in Table 7-2. These classes have test procedures associated with them, as shown in Table 7-3. These two tables indicate appropriate EMC tests to be conducted on any item of equipment. The test procedures indicated are described in MIL-STD-462, but the test limits are given in MIL-STD-461A.

Table 7-2 Classes of Equipment

Class No.	Description
I	Communication-electronic (C-E) equipment Any item, including subassemblies and parts, serving functionally in electromagnetically generating, transmitting, conveying, acquiring, receiving, storing, processing or utilizing information in the broadest sense. Subclasses are:
IA	Receivers using antennas
IB	Transmitters using antennas
IC	Non-antenna C-E equipment (such as counters, oscilloscopes, signal generators, RF and audio test equipment, computers, power supplies, digital equipment, electrically operated cameras and projectors, wire terminal image interpretation facilities, photographic processing equipment, and other electronic devices working in conjunction with classes IA and IB).
ID	Electrical and electronic equipment and instruments that would affect mission success or safety if degraded or malfunctioned by internally generated interference or susceptibility to external fields and voltages such as auto-pilots, infrared devices, flight instruments, auto-compasses and electronic engine control devices.
II	Non-communication equipment, Specific subclasses are:
IIA	Non communication-electronic equipment - Equipment in which RF energy is intentionally generated for other than information or control. Examples are ultrasonic equipment, medical diathermy equipment, induction heaters, RF stabilized arcwelders, RF power supplies, and uninterruptible power units (both rotary and solid state).
IIB	Electrical equipment - Some examples are electric motors, handtools, office and kitchen equipment, laundry and repair shop equipment, and lithographic processing equipment.

Table 7-2 Classes of Equipment Continued

Class No.	Description
IIC	Accessories for vehicles and engines - Electrically and mechanically driven and engine electrical accessories such as gauges, fuel pumps, regulators, windshield wipers, turret motors, magnetos and generators, when tested off the vehicle or engine. Applicable only to accessories for use on items of classes IIIA and IIIB.
III	Vehicles, engine-driven equipment
IIIA	Tactical vehicles - Included are: armored and tracked vehicles, off-the-road cargo and personnel carriers, assault and landing craft, amphibious vehicles, patrol boats, mobile railway and maintenance-of-way equipment, and all other vehicles intended for installation of tactical C-E equipment.
IIIB	Engine-generators - Those supplying power to, or closely associated with, C-E equipment.
IIIC	Special-purpose vehicles and engine-driven equipment - Those intended for use in critical communication areas such as airfields, missile sites, ships forward areas, or in support of tactical operations. Examples are fire engines, aircraft service vehicles, pumps, blowers, and bulldozers and other construction equipment, harbor tugs, floating repair shops, self-propelled barges, and fork-lift trucks.
IIID	Administrative vehicles - Basically of civilian character, not intended for use in tactical areas or in critical areas covered by class IIIC and not intended for installation of communication equipment. Examples are sedans, and other material handling equipment, whether engine-driven or electrically driven.
IV	Overhead power lines

Table 7-3 Test Requirements Applicable to Equipment Classes

	Equipment Class												Description of Test Method
	IA	IB	IC	ID	IIA	IIB	IIC	IIIA	IIIB	IIIC	IIID	IV	
CE01	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	30 Hz to 20 kHz, Power Leads
CE02	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	0.03 to 20 kHz, Control and Signal Leads
CE03	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	0.02 to 50 MHz, Power Leads
CE04	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	0.02 to 50 MHz, Control and Signal Leads
CE05	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	30 Hz to 50 MHz, Inverse Filter Method
CE06	Y	Y	N	N	N	N	N	N	N	N	N	N	10 kHz to 12.4 GHz, Antenna Terminal
CS01	Y	Y	Y	Y	N	N	N	N	N	N	N	N	0.03 to 50 kHz, Power Leads
CS02	Y	Y	Y	Y	N	N	N	N	N	N	N	N	0.05 to 400 MHz, Power Leads
CS03	Y	N	Y	N	N	N	N	N	N	N	N	N	30 Hz to 10 GHz, Intermodulation
CS04	Y	N	Y	N	N	N	N	N	N	N	N	N	30 Hz to 10 GHz, Rej. of Undes. Sig. (2-Sig Gen Method)
CS05	Y	N	Y	N	N	N	N	N	N	N	N	N	30 Hz to 10 GHz, Cross Modulation
CS06	Y	Y	Y	Y	N	N	N	N	N	N	N	N	Spike, Power Leads
(T) CS07	Y	N	Y	N	N	N	N	N	N	N	N	N	Squelch Circuits
CS08	Y	N	Y	N	N	N	N	N	N	N	N	N	30 Hz to 10 GHz, Rej. of Undes. Sig. (1-Sig Gen Method)
RE01	Y	Y	Y	N	Y	N	N	N	N	N	N	N	0.03 to 30 kHz, Magnetic Field
RE02	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	14 kHz to 10 GHz, Electric Field
RE03	N	Y	N	N	N	N	N	N	N	N	N	N	10 kHz to 40 GHz, Spurious and Harmonics, Radiated Technique
(T) RE04	Y	Y	Y	N	Y	N	N	N	N	N	N	N	0.02 to 50 kHz, Magnetic Field
RE05	N	N	N	N	N	N	N	Y	Y	Y	N	N	150 kHz to 1 GHz Vehicles and Engine Driven Equipment
RE06	N	N	N	N	N	N	N	N	N	N	N	Y	Overhead Power Line Test
RS01	Y	Y	Y	Y	N	N	N	N	N	N	N	N	0.03 to 30 kHz, Magnetic Field
RS02	Y	Y	Y	Y	N	N	N	N	N	N	N	N	Magnetic Induction Field
RS03	Y	Y	Y	Y	N	N	N	N	N	N	N	N	14 kHz to 10 GHz, Electric Field
(T) RS04	Y	Y	Y	Y	N	N	N	N	N	N	N	N	14 kHz to 30 MHz

Y = Test shall be performed as described in MIL-STD-462 or the approved test plan.
N = Test does not have to be performed unless required by the test plan or procuring activity.

Table 7-4 Index of Measurement Procedures

Method	Title
CE01	Conducted Emission, 30 Hz to 20 kHz, Power Leads
CE02	Conducted Emission, 30 Hz to 20 kHz, Control and Signal Leads
CE03	Conducted Emission, 20 kHz to 50 MHz, Power Leads
CE04	Conducted Emission, 20 kHz to 50 MHz, Control and Signal Leads
CE05	Conducted Emission, 30 Hz to 50 MHz, Inverse Filter Method
CE06	Conducted Emission, 10 kHz to 12.4 GHz, Antenna Terminal
CS01	Conducted Susceptibility, 30 Hz to 50 kHz, Power Lead
CS02	Conducted Susceptibility, 50 kHz to 400 MHz, Power Lead
CS03	Conducted Susceptibility, 30 Hz to 10 GHz, Intermodulation, Two Signal
CS04	Conducted Susceptibility, 30 Hz to 10 GHz, Rejection of Undesired Signals at Input Terminals (2-Signal Generator Method)
CS05	Conducted Susceptibility, 30 Hz to 10 GHz, Cross-Modulation
CS06	Conducted Susceptibility, Spike, Power Leads
(T) CS07	Conducted Susceptibility, Squelch Circuits
CS08	Conducted Susceptibility, 30 Hz to 10 GHz, Rejection of Undesired Signals at Input Terminals (1-Signal Generator Method)
RE01	Radiated Emission, 30 Hz to 30 kHz, Magnetic Field
RE02	Radiated Emission, 14 kHz to 10 GHz, Electric Field
RE03	Radiated Emission, Spurious and Harmonic Emissions, 10 kHz to 40 GHz
(T) RE04	Radiated Emission, 20 Hz to 50 kHz, Magnetic Field
RE05	Radiated Emission, 150 kHz to 1 GHz, Vehicles and Engine Driven Equipment
RE06	Radiated Emission, 14 kHz to 1 GHz, Overhead Power Lines
RS01	Radiated Susceptibility, 30 Hz to 30 kHz, Magnetic Field
RS02	Radiated Susceptibility, Magnetic Induction Fields
RS03	Radiated Susceptibility, 14 kHz to 10 GHz, Electric Field

MIL-STD-462

MIL-STD-462 establishes techniques to be used for measurement and determination of the electromagnetic emission and susceptibility characteristics of electrical, electronic, and electromechanical equipment, as required by MIL-STD-461. Test setups are given in block diagram form for each emission and susceptibility test, with explanations of how to conduct each measurement. The limits that apply to each test are given in MIL-STD-461A. The tests are listed in Table 7-4, wherein the method designators are coded as follows:

CE	-	Conducted emission
CS	-	Conducted susceptibility
RE	-	Radiated emission
RS	-	Radiated susceptibility
(T)	-	Tentative

MIL-STD-463

This standard contains general interference definitions, abbreviations, and acronyms used in MIL-STD-461 and MIL-STD-462. Definitions, abbreviations, and terms are described as used in this and the other standards. A fundamental knowledge of the principles of interference on the part of the reader is assumed.

MIL-STD-469

The expanding use of radar for various military purposes, with attendant expansion of demands on the electromagnetic spectrum, has created an urgent need for the formulation and application of more effective standards of frequency management. As an initial step, adoption of minimum engineering design requirements was considered necessary.

The design requirements and criteria of MIL-STD-469 are not intended to inhibit research in the development of new, more effective radar systems. The engineering design requirements are established to control the spectral characteristics of all new radar systems operating between 100 megahertz and 40 gigahertz in an effort to achieve electromagnetic compatibility and to conserve the frequency spectrum available to military radar systems.

Required Documents

Requirements for two plans are specified in MIL-STD-469–a Design Criteria Plan and a Test Plan.

The Design Criteria Plan is to be submitted to the procuring activity for approval, and unless otherwise specified by the procuring activity, is to include the following:

a. Name, responsibility, and authority of the individual who will implement the contractor's design program
b. Number and experience of full-time and part-time radar design and EMC personnel assigned to the program

c. Organization chart showing all program personnel
d. Design aspects of the system as related to the requirements specified herein. Specific items to be discussed include:
    1. General design philosophy and reasons for the proposed approach
    2. Anticipated problems and proposed methods for solution
    3. Methods of implementing the design
e. Detailed description of facilities, on hand and to be procured (identified separately), that will enable contractor to determine compliance with the requirements stated herein
f. Methods of reviewing design with subcontractor

When required by the contract or order, a Test Plan must be submitted to the procuring activity for approval before testing, detailing the tests to be performed to determine compliance with requirements of MIL-STD-469. The Test Plan includes:

a. Test conditions and procedures for the system, and the sequence of operation during the tests
b. Implementation and application of test procedures, including modes of operation, control settings, and monitored points
c. Nomenclature and general characteristics of test equipment to be used
d. Types and methods of calibration of standards and calculations to show expected accuracy of each
e. Dummy loads, filters, dummy antennas, signal samplers to be used, and their descriptions
f. Readout and detector functions to be used
g. Details of test setups, test site procedures, etc. Maximum use of photographs and drawings is required
h. Expected accuracy of measurement
i. Nomenclature and description of test sample
j. Personnel required, both designated Government representative and the contractor

Testing Requirements

MIL-STD-469 also lists recommended test equipment and the test methods and procedures to be used for the design of new military radar systems. Limits pertinent to each test are presented in the limits paragraph of the document. In effect, this document supplements MIL-STD-461 and MIL-STD-462 for radar equipments. MIL-STD-469 will be required in addition to MIL-STD-461 for radar equipments.

Measurements presented in MIL-STD-469 are grouped into three main categories. These three categories, and the tests in each, are:

Radar transmitter measurements
    Radar transmitter frequency tolerance
    Radar system tuneability

Radar emission bandwidth
Radar transmitter spurious radiations
Radar receiver measurements
Receiver response characteristics
Receiver radiation
Antenna measurements
Radar antenna sidelobe suppression

MIL-STD-449

Successful operation of most military systems depends upon the exchange of information through electromagnetic radiations. Such operation is degraded by interfering radiations in the normal environment. To predict the mutual interference effects of electronic equipment, more quantitative information is needed. Entire transmitter spectra need to be known as well as the susceptibility of receivers to the various frequencies, powers, and modulations in their operational environments.

MIL-STD-449 establishes uniform measurement techniques useful in determining the spectral characteristics of radio-frequency transmitters and receivers. The goal is to ensure the compatibility of present and future systems by providing data necessary for predicting interference during design and development stages.

The data obtained from the measurements described in this standard will comprise one of the principal aids for:

a. Predicting the performance of equipment and systems in an operational electromagnetic environment
b. Predicting the effect of a particular equipment or system on the electromagnetic environment of other equipments or systems.

This data will be used for ECAC data files and in applying for frequency allocations. This data will also aid in establishing the characteristics required of new equipment for compatible operation in present and future electromagnetic environments.

This radio-frequency measurement standard applies to all equipments and systems designed to emit or respond to electromagnetic energy in the radio-frequency range of 14kHz to 12GHz. This standard does not necessarily apply to all parameters of all systems.

The measurements of spectral characteristics specified in MIL-STD-449 are:

a. Radio-frequency characteristics at equipment terminals (closed system) - These measurements disclose the radiation spectral characteristics at the antenna terminals of equipments that either transmit or receive radio-frequency energy.
b. Antenna-radiated radio-frequency output (open field) - These measurements disclose the radio-frequency spectral characteristics of a complete equipment, including the effects of transmission line and antenna space distribution pattern.

c. Receiver susceptibility - These measurements determine the susceptibility of receiving equipment to radiation at other than the desired operating frequency. Such measurements are used to determine the spurious-response characteristics of receivers and are referred to in such terms as "unwanted response," "spurious-response rejection ratio," "intermediate frequency rejection ratio," and "off-frequency sensitivity."

MIL-E-6051D

This specification outlines the overall requirements for electromagnetic compatibility in aerospace systems, including control of the system electromagnetic environment. lightning protection, static electricity, bonding, and grounding. It applies to complete systems, including all associated subsystems and equipments. The following requirements are covered in this specification.

Electromagnetic Compatibility Advisory Board (EMCAB)

An electromagnetic compatibility advisory board monitors the system Electromagnetic Compatibility Program, provides means of expediting solutions to problems, and establishing high-level channels of coordination.

EMC Control Plan

The system EMC Control Plan contains the details of the system Electromagnetic Compatibility Program. It is submitted to the procuring activity for review and approval. The Control Plan is prepared and submitted in accord with requirements of the contract. Compliance with it, after approval, is a contractual requirement.

EMC Test Plan (EMCTP)

The EMCTP, upon approval of the procuring activity, provides for a system EMC test, an EMC general acceptance test, and missile and avionics systems tests.

Test Report

A complete test report conforming to MIL-STD-831 is required in accord with MIL-E-6051 and the contract. The report contains complete information on all applicable tests and other information required by the EMC Test Plan.

MANAGEMENT IMPLEMENTATION

Management has a key role in the application of EMI standards. This role begins at the inception of a project, whether large or small. The procedure for fulfillment of this role will vary with the particular project or program involved,

but will include some and perhaps all of the areas discussed in the following paragraph.

The first step is modification of the general standards to apply to various portions of the program as part of contract negotiations. The procuring activity must define general requirements to be met, based usually upon a Technical Development Plan (TDP). The limits and criteria to be incorporated in a specification depend on the ultimate use of the proposed system, the type of system, and what is to be accomplished. It is conceivable (though not probable) that no EMC requirements are necessary in the specification, i.e., that EMI is not a factor. On the other hand, it is possible that the ultimate EMC requirements of the system cannot be met with an existing standard. If the latter situation exists, there are two alternatives: to modify an existing standard or to write a system EMC specification that details the EMC requirements.

In practice, both of these approaches are used. An existing standard is modified to some extent almost every time it is used, since some tests may not be applicable or some setups must be altered to fit the equipment. The modifications will range from trivial to substantial.

New specifications may be prepared for systems or programs that current EMI standards do not adequately cover. For example, a complete EMI specification was prepared for the Titan missile system, to cover both individual equipments and assemblies.

From a time and cost standpoint, it is obvious that the first choice is preferred, but the second may be justifiable under some circumstances. This is one example of a case where good technical management with EMI experience is required. The choice between modifying an existing document and preparing a new one is difficult, necessitating careful analysis of the technical requirements of the system as well as an appreciation of cost and scheduling problems. The EMI effort must be kept in proper perspective.

Modification of an existing standard will be satisfactory in most instances. Assuming this to be the case, several steps must be taken. First, the tests pertinent to the program must be selected and the rest deleted. Since current EMI standards are fairly comprehensive, it is probable that not all parts of the standard will be applicable to a particular program.

Second, the limits and levels specified should be examined in light of specific requirements. These may be too lax or too severe for the given program or parts of the program. The frequency ranges may be too broad or too narrow. Each of these matters must be considered.

Third, technical management must be certain that all tests required to ensure overall compatibility are included. In some instances, a complete system operational check during which margins of safety are determined at critical points may be necessary; this is generally the philosophy of MIL-E-6051.

In some cases, EMI specification requirements may be adapted to fit a particular portion of a program. For example, certain high-level transients (such as those caused by the change-over from ground to vehicle power) may be tolerable at launch but not later in the flight. As another example, consider the signal level available to a receiver at take-off, and the level of the same signal

later in flight. The receiver can probably tolerate higher level extraneous signals at launch than later due to the change in signal levels. This type of logical consideration is necessary for an optimum EMI control program.

Coordination of EMI tests with the over-all program is another area that must be considered early in program management because it is possible that certain units or subsystems will require modification after initial EMI tests.

A most difficult problem facing management in the enforcement of an EMI specification is that of the "waiver." A waiver is written authorization to accept an item, equipment, or system which during production, or after having been submitted for inspection, is found to depart from specified requirements. Often a problem will arise late in a program when some key unit, though functioning properly, causes a compatibility problem that limits system performance. Time or money may not be available to perform the necessary modification or redesign. The ultimate decision of whether to waive the requirement or delay the program requires a capable program management decision.

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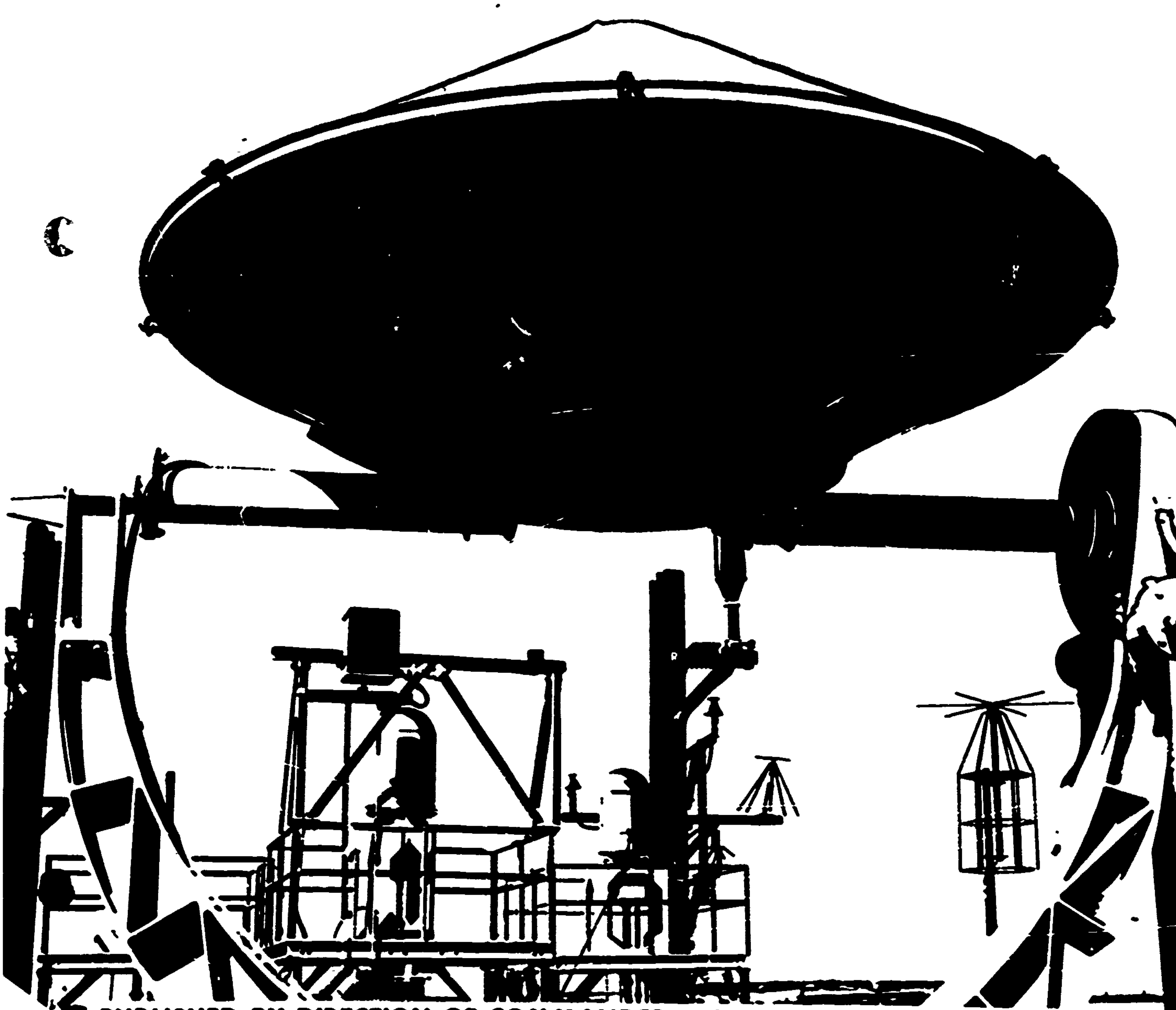
5. *DoD EMC Standardization Program Analysis, FY 70-74 Naval Electronics Systems Command, January 1970*

NAVAIR 5335

NAVAL AIR SYSTEMS COMMAND

ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 8



PUBLISHED BY DIRECTION OF COMMANDER, NAVAL AIR SYSTEMS COMMAND

CHAPTER 8
ACHIEVEMENT OF ELECTROMAGNETIC COMPATIBILITY

CONTENTS

ILLUSTRATIONS

EMC REQUIREMENTS AT FOUR LEVELS

Naval weapon systems continue to become more advanced in concept and more complex in functional configuration. Operational effectiveness of these systems is an important factor to tactical success, and it is increasingly difficult to achieve because of dependence on sharing the electromagnetic spectrum with a multitude of other occupants. Performance effectiveness of systems calls for meeting design and operational requirements for compatibility of the components of a system with each other and for compatibility of the system with its environment.

To meet overall EMC requirements, electromagnetic compatibility must be achieved at each of four levels:

(1) Circuit element or electronic part
(2) System component or subsystem
(3) System
(4) System-to-system or system-to-environment

A system is considered to be electromagnetically compatible when it can perform its mission in its intended environment without being degraded below its specified effectiveness level by the effects of electromagnetic interference (EMI).

EMC AT ELECTRONIC PART LEVEL

Many electronic parts have characteristics that influence electromagnetic compatibility, either passively or actively. With today's increase in part density, complexity, and sensitivity, a number of previously insignificant characteristics have become important when considered with regard to possible degradation of EMC. Even a seemingly simple circuit part may exhibit complex impedances, resonances, nonlinearities, and stray coupling characteristics. When a part functions as a circuit element, it may be capable of contributing noise, voltage transients, stray fields, and other effects. For this reason, careful attention should be given to the EMC characteristics of electronic parts that go into the design of an equipment.

Resistors

A resistor, when functioning as a current-carrying circuit element, and in proximity to other parts and to a ground return, presents a complex impedance

as shown in the equivalent circuit of Figure 8-1. The desired circuit characteristic of body resistance R_B is modified by the effects of the other characteristics present as a result of construction and circuit application. Lead resistance R_L and inductance L_L are negligible except at UHF and above. Input and output shunt capacitance C_I and C_O depend in part on proximity of the resistor to other circuit parts. Body inductance L_B and shunt capacitance C_S depend upon type of construction, with the inductance being greatest in the wirewound types. Inductance of wirewound resistors may be decreased by using bifilar winding, but shunt capacitance is increased thereby. Body resistance R_B varies with frequency because of skin effect, as do the impedance values presented by inductive and capacitive characteristics.

Resistor noise voltage E_n is attributable to two factors: thermal noise due to ambient temperature, and current noise due to random variations in current paths. In general, resistor noise is greatest in composition types and least in wirewound or metal film types.

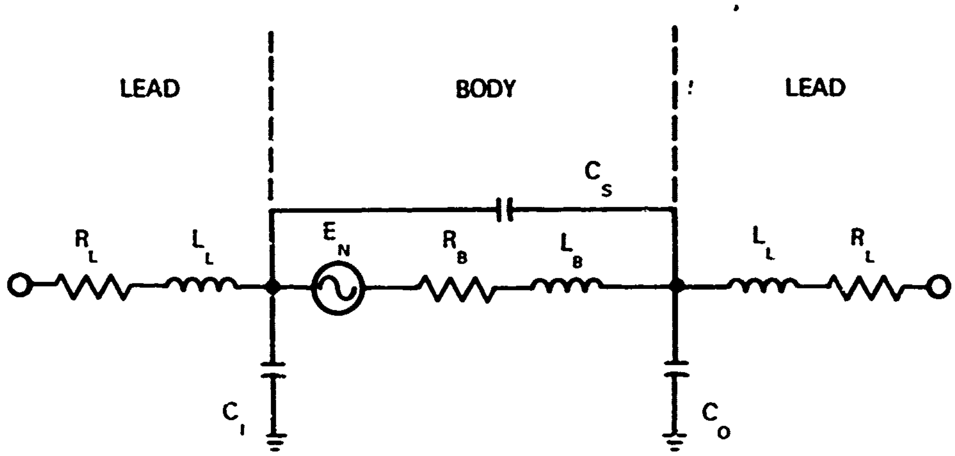


FIGURE 8-1 LUMPED EQUIVALENT CIRCUIT OF A RESISTOR

Capacitors

A capacitor, when functioning as a circuit element, presents a complex impedance as shown in the equivalent circuit of Figure 8-2. The desired circuit characteristic of body capacitance C_B is modified by the effects of other characteristics present as a result of construction styles and materials.

In most capacitors, lead inductance L_L and plate inductance L_P act with body capacitance C_B to form a resonant circuit at some frequency. Inductance L_P is greatest in rolled foil capacitors and least in ceramic or mica capacitors. Lead resistance R_L and charging resistance R_C (attributable to resistivity of the plate material and hysteresis of the dielectric material), as well as dielectric leakage resistance R_D, affect the dissipation factor and consequently the Q and

heating effects on the capacitor.

A capacitor affects EMC design by presenting a circuit impedance other than purely capacitive. Of particular concern is the ability of a capacitor to act as a self-resonant circuit and thereby contribute to parasitic oscillation. A capacitor can also generate circuit noise, which is caused by stress effects in the dielectric material or by improper adhesion of conducting material to the dielectric.

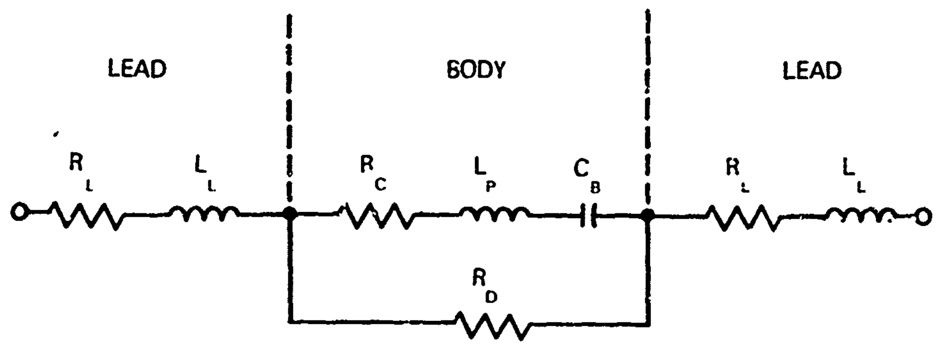


FIGURE 8-2 LUMPED EQUIVALENT CIRCUIT OF A CONVENTIONAL CAPACITOR

Inductors

An inductor functioning as a circuit element presents a complex impedance to the circuit. An inductor has inductance, resistance, capacitance between turns, capacitance between layers of multilayer inductors, and capacitance to shield, ground, or isolate adjacent windings. Metallic core materials increase resistive losses and can change the effective inductance.

An inductor can affect EMI design by exhibiting undesired circuit effects. Its self-inductance can act with distributed and stray capacitance to form a resonant circuit, thereby contributing to parasitic oscillation. It can couple energy into or from adjacent circuits through stray mutual inductance and magnetic fields. It can also couple energy into or from adjacent circuits through stray capacitance. This capacitive coupling must be minimized by interposing appropriate capacitance-reducing shields between windings. Inductors using magnetic core materials can also contribute to EMI by presenting nonlinearities caused by core saturation.

Relays and Switching Devices

Any circuit device that interrupts an electrical current can cause transients capable of producing EMI. Common switching devices include manually-operated switches, circuit breakers, thermostats, relays, motor or generator commutators, vibrators, choppers, tube or semiconductor switches,

and saturable reactors. The circuit effect of a switch is to bring about a rapid change of impedance, from very low (ideally zero) to very high (ideally infinite). The circuit being switched must therefore adapt quickly to new circuit conditions. For unsuppressed switches, an arc is produced that is almost proportional to voltage at the switch contacts. Switching transients produce a damped train of oscillations which are broadband in nature and therefore a source of EMI.

When a switch opens a circuit to an inductive load such as a relay solenoid or a motor, collapse of the load magnetic field can induce an EMF in the winding that causes a voltage many times the supply voltage to appear across the opening contacts. This large transient adds to the severity of EMI. Because motors and relay solenoids are usually connected to their controlling switches by relatively long connecting wires, the resultant EMI is likely to be widely distributed unless it is controlled. The usual control measures consist of semiconductor devices used as voltage spike suppressors at the load, or resistor-capacitor networks either at the switch or at the load to damp the transient waveform.

To meet EMC requirements, a new generation of switches has been developed for reducing switching transients. These switches use solid state devices which, in AC circuits, turn the circuit on at the time of zero voltage crossing and turn the circuit off at the time of zero current crossing. The switch for DC circuits ramps the circuit closed and ramps it open. This prevents sudden surges which cause interference over a broad portion of the spectrum.

Conductors and Cables

A conductor is a material that permits electrical currents to flow with a minimum of impedance between two points of potential difference. Wires, straps, and structural members commonly used for conductors all exhibit resistance, inductance, and capacitance. Resistance is a function of conductor materials and effective cross-section area. However, the conductor also has inductive properties, and its effective cross-section area varies with frequency because of skin effect. Increase of conductor resistivity and inductive reactance with frequency must be taken into account for EMC planning purposes.

Conductors also can couple energy into or from adjacent circuit elements through inductive and capacitive coupling. Cable runs, wiring harnesses, and circuit layouts must be planned with consideration of the possibility of such EMI coupling. Mutual coupling between conductors is minimized by:

(1) Shielding measures, as for coax. (Shielding effectiveness depends upon porosity and conductivity of the shielding material.)

(2) Physical separation. (Reduction of capacitive coupling through physical separation should take into account the dielectric constants of the insulating materials.)

(3) Twisting or transposing wires, or use of balanced lines.

(4) Avoiding wire arrangements that result in inductive coupling loops.

Vacuum and Gas-Filled Tubes

The purpose of vacuum and gas-filled tubes (except diodes) is to permit a small change of input potential to produce large changes of current in the output circuit. When changes in the output are not linear with respect to changes in the input, EMI difficulties can arise from harmonics, intermodulation, cross-modulation, switching transients, and phase or amplitude distortion. Diodes are normally operated in their nonlinear region about cutoff. Other tubes may be operated in a nonlinear region intentionally, as for mixers, class B or C amplifiers, oscillators, amplitude limiters, switch or gate tubes, and detectors.

Any tube can operate in a nonlinear manner if the applied signal is large enough to drive the tube either into saturation or into cutoff. For example, if the RF stage of a receiver is driven into a nonlinear portion of its operating characteristic curve by a signal from a nearby transmitter, EMI can occur in several ways:

(1) Harmonics will be generated which may affect other portions of the receiver, e.g., interact with oscillator harmonics to produce interference.

(2) The harmonic energy may be coupled back onto the antenna or multi-coupler to interfere with other receivers.

(3) The RF stage may act as a mixer so that the interfering signal intermodulates with the wanted signal, or cross-modulates with another unwanted signal that might otherwise have been rejected.

The above contributions to EMI are not limited to receiving tubes; when the RF amplifier of a transmitter is coupled to an antenna, received signals on the antenna see the tube as a nonlinear circuit element. Harmonic, inter-modulation, and cross-modulation products are produced in the same way.

Tubes contribute to circuit noise because of irregularities in cathode emission and because of current division in multi-element tubes. Hum may also be present because of AC on the heaters, especially if the cathode goes positive with respect to the filament. Mechanical vibration of the tube can cause microphonic changes in tube current and thereby produce interference.

Gas-filled tubes are greater noise generators than vacuum tubes because of ion bombardment and because of switching about the ionization potential. Gas tubes, which have circuit applications as rectifiers, controllers, keyers, and regulators, require special attention to keep the EMI they generate from reaching susceptible circuits.

Transistors and Other Semiconductors

Transistors are free of the filament hum and microphonic effects present in tubes, but they do contribute to EMI. A transistor operated in its nonlinear region will cause harmonics, intermodulation, and cross-modulation in the same way as a tube and will do so at much lower signal levels. A semiconductor switched about its cutoff point will also produce transient surges because of

minority carrier storage. This is a particular trouble point in high-voltage rectifiers.

For small-signal proportional amplifier applications, technology has produced several semiconductor devices that generate less noise than tube devices. Of special note are the parametric amplifier, tunnel diode, and field effect devices. The point contact diode has long been the best available low-noise microwave mixer.

Semiconductor devices used in switching may also offer a means of reducing EMI that would be caused by transients. Transistor switches can control the rise and fall of the switching wavefront, thereby eliminating the EMI-producing spike by shaping the turn-on and turn-off time of the switching transistor. There are problems however; in effect, the transistor absorbs the switching transient, and then must dissipate it in the form of heat. Switching circuits using SCR's can also be accidentally triggered into conduction capacitively by stray noise voltages that need not reach triggering potential if its wavefront is steep enough.

EMC AT COMPONENT AND SUBSYSTEM LEVEL

Consideration for control of EMI enter into the design of black-box components that make up a subsystem, and into the design of subsystems that make up a system. Selection of parts, circuit layout and configuration, and choice of design parameters should be based in part on electromagnetic compatibility requirements.

A sample plan for testing EMC characteristics of an individual component or subsystem is shown in Appendix C. This should indicate the test procedures, test equipments, and test data required at the system component and subsystem level.

Circuits and Combinations of Parts

Circuit configurations and choice of parts should be planned to minimize EMI. The following guidelines indicate some of the possibilities:

(1) A capacitor with appreciable inductance or resistance should not be used either for bypassing or interstage coupling in VHF/UHF applications.

(2) Avoid using chokes and capacitors capable of self-resonance at critical EMI frequencies.

(3) An oscillator whose output waveform is as nearly sinusoidal as possible should be used to avoid problems with harmonics.

(4) Avoid using the same value of choke in both the plate and the grid circuits of an amplifier stage because it invites parasitic oscillation.

(5) All ground connections in each stage should return by separate leads to a single common ground point. Ground leads should not form a common inpedance path for two or more circuits.

(6) Parts having low EMI potential should be chosen in preference to parts

that are prolific generators of EMI. For example, a brushless induction motor should be used in blower applications in preference to a brush type motor.

Circuit Layout and Configuration

Circuit layout and configuration should provide separation and isolation of susceptible circuits from EMI sources, and confinement of EMI sources to nonsusceptible areas. Low level stages of high susceptibility, such as speech amplifiers, may have to be enclosed in shields and kept separate from all other circuits, and all leads penetrating the shield appropriately filtered. Similar isolation measures should be applied to sources of EMI. For example, a power supply or chopper circuit should be shielded and filtered to prevent the EMI it generates from reaching other circuits. Orientation and placement of transformers should be planned to minimize mutual magnetic coupling. Wiring runs should be planned so that susceptible wires are not brought close to EMI-generating circuits, or so that EMI-bearing wires are not brought close to susceptible wires or circuits.

Choice of Design Parameters

Design parameters should be chosen with consideration for electromagnetic compatibility. A decision to use high power and short pulses in radar, for example, must be weighed against the EMI that the radar can cause. Design parameters should be selected to provide effective performance while controlling EMI. Following are some guidelines for selecting design parameters to control EMI:

(1) Choice of operating frequency should be based on compatibility of receiver and transmitter components with other components of the system and with the environment in which the system will operate. Choice of operating frequency must be based on the availability of frequencies for assignment by the agency having cognizance.

(2) Frequencies to be used for processes within a system component must be chosen with a view to possible incompatibilities, both within the component and external to it. The frequencies of IF amplifiers, oscillator fundamentals, delay line modulators, power supply choppers, magnetic tape erase and bias oscillators, horizontal CRT sweep oscillators, digital computer clocks, and frequency synthesizers are all capable of spurious emission or spurious susceptibility. Design plans should provide for compatible combinations of internal frequencies.

(3) Bandwidth chosen both for transmission and for reception should be no greater than needed to meet performance requirements. Increased bandwidth invites adjacent-channel interference. Bandwidth requirements represent a trade-off against data rate requirements, which in turn must consider reliability in the presence of EMI.

(4) Choice of power output

EMC AT SYSTEM LEVEL

The quest for electromagnetic compatibility is not satisfied merely by designing an item such as a HF radio set so that it is compatible within itself and with its companion components of the communications subsystem. Compatibility is required of the widely diverse combinations of subsystems that make up the complete aircraft and its support equipment.

System-wide compatibility has not been achieved if keying the UHF transmitter interferes with the autopilot and causes the aircraft to execute snaprolls. System compatibility requires that all subsystems, components, and parts–not just avionics–meet EMC specifications. The aircraft power generation, distribution, and lighting subsystems should not cause interference to the navigation, communication, and flight stabilization subsystems. Airframe wiring and control actuators should not serve as transmission media to couple interference between two avionics components, or between an outboard weapon station and a navigation subsystem. Bonding and grounding throughout the aircraft should be designed to satisfy EMC requirements at all frequencies to which the system may be exposed.

SYSTEM-TO-SYSTEM OR SYSTEM-TO-ENVIRONMENT COMPATIBILITY

Aircraft are expected to operate in proximity to other aircraft, ships, and ground facilities. Design considerations should plan for compatibility of aircraft systems with other aircraft that may be of the same or of different system configuration, in formation or nearby. Compatibility planning also calls for consideration of shipboard and ground systems that comprise the aircraft environment and which may introduce EMI into the aircraft system. This requires analysis of EMC details based on a study of mission profile and operational requirements.

EMC DESIGNING AND PLANNING CONSIDERATIONS

Designing and planning for electromagnetic compatibility should begin in the earliest stages of program planning. The first step in defining system characteristics in a Tentative Specific Operational Requirement (TSOR) should include EMC as one of the requirements. A TSOR sets forth the expected mission envelope, often with provisions for missions beyond the basic one. This establishes the needed system capability and consequently fixes interference tolerance limits on which EMC design is based. As planning and designing continue through to the finished product, EMC requirements should be represented at each stage.

PROJECT EMC CONTROLS

Requirements for control of EMI form a part of any significant program involving development or procurement of electrical or electronic devices, equipments, or systems. Contractors responding to a Request For Proposal (RFP) are expected to describe their organizational methods, personnel, test facilities, engineering capabilities, and quality controls for meeting EMC standards and specifications. The successful bidder will be required to submit an EMC Control Plan and an EMC Test Plan for the projected system. If it is part of the contract, he will also be required to set up an Electromagnetic Compatibility Advisory Board (EMCAB) to review design details, test procedures, and test results, and to recommend changes or alternate measures where indicated.

EMC SPECIFICATIONS AND STANDARDS

A series of military specifications and standards has recently been revised, updated, and consolidated to conform to the needs of the DoD EMC Program as promulgated by the Department of Defense Directive 3222.3 and further implemented by the secretaries of the military departments. Specifications and standards are continually reviewed and updated as EMC requirements become better defined, as better test equipments and test techniques are developed, as systems become more complex and critical, and as requirements for access to the electromagnetic spectrum become more stringent.

For the most part, military specifications and standards represent minimum requirements for general classes of equipments or systems. Before procuring a system or equipment, it must be determined whether the generalized military specifications and standards relating to EMC adequately fit the mission envelope of the system or equipment being planned. Specifications to be invoked, and variations to them, are a subject of contract negotiations.

EMC CONTROL PLAN

Major procurement or development contracts require the contractor to submit an electromagnetic compatibility control plan as part of contract data. The EMC Control Plan is a formal document describing the contractor's entire EMC program for the project, and sets forth his management methods, organizational responsibilities, design criteria, test procedures and limits, and related matters associated with EMC control of the contract and product.

Sample EMC Control Plans appear in Appendix A and Appendix B. The EMC Control Plan sets forth the details of EMC organization and responsibilities, and state the applicability of standards and specifications. The EMC Control Plan must be approved by the procuring activity before it is put into effect.

TECHNOLOGICAL ADVANCEMENT OF DESIGN AND DESIGNERS

So that people concerned with EMC can keep abreast of rapidly advancing

scientific developments, continuing education and indoctrination are needed. This manual forms part of such a program. A current library of EMC publications should be available to EMC personnel, who should continue to update their skills through participation in professional societies and through study of current reports on the subject.

The pace of technological advancement requires each new system to undergo appreciable updating of design because of the inevitable increases in complexity of electromagnetic systems and increases in occupancy of the spectrum. The Electromagnetic Compatibility Analysis Center (ECAC) is organized to provide the military departments with analysis and prediction capability. ECAC maintains data files of spectrum signatures of previously tested equipments, as well as environmental data useful for the geographical study of spectrum occupancy.

EQUIPMENT/SYSTEMS ANALYSIS

During design and analysis, an aircraft should be considered as a complete system. It is not enough to design a radar that detects and tracks targets to specified limits; the radar must also be designed to meet specifications while communications. navigation, missile guidance, and other system components are operating. Furthermore, operation of the radar must not degrade other system components below their specified level of performance.

There are many design factors to which EMC is interrelated. For this reason, EMC design engineers should maintain liaison with all production and management departments. Airframe design is concerned with bonding and grounding requirements for EMC, compatible antenna locations and look angles, and with weight and moment compensation for devices which must be added to achieve EMC. Electromechanical control actuators, lighting system, cockpit environment controls, generators, regulators, electrical panel instruments, circuit breaker and switch panels, and a multitude of other devices not considered avionics equipments must enter into the EMC evaluation and analysis. Individual designers may recognize discrete interface points in the chain of radio beam receiver to autopilot to electrohydraulic control actuator, but the duties of the EMC engineer do not stop at an interface. EMC engineering must consider flight safety devices including warning indicators, and must be aware of radiation hazards to personnel (RADHAZ) and hazards of electromagnetic radiation to ordnance (HERO).

A mission profile might require an aircraft to:

(1) Operate ECM search equipment to locate a hostile radar
(2) Acquire and track it with airborne radar
(3) Penetrate the hostile radar perimeter with the aid of airborne screening jammers
(4) Maintain communication with command and with other aircraft in the area
(5) Compute weapon data with the attack/nav computer
(6) Designate the target to the missile system

(7) Guide missiles to the target

Prediction, design, and analysis of EMC must be based on all seven of the above system requirements, and others as well, existing simultaneously. Requirements for spectrum control, shielding, grounding, bonding, filtering, separation of wires and antennas, and inter-equipment blanking and gating programs are made by the EMC control group and communicated to all departments.

EMC CONTROL, TEST, AND EVALUATION CONSIDERATIONS

In the achievement of EMC, control, test, and evaluation are closely related. EMC control is part of project planning and development to ensure that functions are oriented in accord with good EMC engineering. The EMC Control Plan is evidence of this action, and continuous updating of the plan is an indication that EMC control activities are alert to changing requirements and design restraints imposed as the design solidifies.

Test considerations involve development of an EMC Test Plan to demonstrate that EMC control has been successful within the requirements of the contract. The EMC Test Plan and the EMC Test Procedures are formal documents prepared by the contractor and approved by the customer. Approval forms a tacit agreement that the EMC Test Plan and the EMC Test Procedures prove compliance with EMC specifications of the contract.

When the contractor has completed EMC tests required by contract and is satisfied that his design can meet performance specifications, the aircraft is submitted to the Navy for Board of Inspection and Survey (BIS) trials. BIS trials are conducted to determine that the aircraft and its support equipment can meet requirements of the mission envelope of service use.

Evaluation for electromagnetic compatibility appraises the avionic and electrical systems to determine their ability to meet specified EMC requirements. Several types of tests are used for the evaluation: development assist tests, operational evaluations, and research/operational investigations. Development assist tests are projects in which Fleet services are provided by the Navy when a developing agency must conduct tests in an operational environment before continuing with a development effort. Operational evaluations are service acceptance tests that culminate the RDT&E effort for each development. Research/operational investigations are projects using Fleet services for broad research not directly connected with a current equipment development.

IMPLEMENTATION OF ELECTROMAGNETIC COMPATIBILITY PROGRAM

The joint EMC effort of the Navy and industry is to produce weapon systems that will operate as intended within their operational electromagnetic environment. As weapon systems have become more complex, there have been more stringent demands on Navy and industry to implement a sound and

effective Electromagnetic Compatibility Program (EMCP).

A well-managed and coordinated EMCP includes:

(1) EMC Control Plan

(2) EMC Test Plan

(3) EMC Test Procedures Plan

(4) EMC Test

(5) Electromagnetic Compatibility Advisory Board (EMCAB)

A well-managed EMCP will also have an adequate staff of EMC engineers and technicians who are given complete responsibility for meeting EMC requirements of the contract. This responsibility is then backed up with authority to integrate good EMC design practice into the overall design. The control group must be aware of EMC requirements of each specification and standard referred to in the contract. The test personnel must be familiar with test methods required by specifications and standards and must also know the significance of the test methods so that they can tailor these tests to the test objectives.

EMC INFLUENCE ON COST EFFECTIVENESS AND FLIGHT SAFETY

The influence of EMC requirements on cost effectiveness has been shown in the EA-6A and EA-6B programs. The EA-6A program was funded and contracted without any funding for EMC. The contractor had included an EMC program in his bid but this was cut out to bring costs down. The result of this economy became painfully evident at the BIS trial when intrasystem interference degraded and in some cases negated performance of subsystems. This required a fix-it program so that the EA-6A could meet operational requirements effectively.

The EA-6B program was funded for EMC in the initial stages. The contractor carried out an effective EMCP with the result that EMC problems were largely eliminated before BIS trials. Furthermore, the EA-6B exceeded performance requirements by such a wide margin that operational performance was superior to design goals.

A most important aspect of EMC is flight safety. If an aircraft weapon system cannot fly safely because of lack of EMC, the entire system is a failure. The problem may be in interference to aircraft control functions, or the navigation system. Less serious interference may upset the radio aids to navigation. Interference to the communications system may be a flight safety hazard but less serious than the preceeding types of interference. An effective EMCP will eliminate flight safety hazards due to electromagnetic interference (EMI).

Lightning protection is another factor in flight safety considerations. A complete EMC program will include consideration of lightning hazards and the magnitude of lightning currents which may be induced in the airframe as well as in the equipment wiring and cabling. Conductors must be selected to accommodate these currents. Sensitive circuit elements such as communication

receiver input stage transistors must also be protected from surge currents that might damage them.

EMC PROBLEMS IN PRELIMINARY DESIGN STAGES

EMC techniques used during the design phase of the project should minimize interference to the extent possible consistent with other requirements of the system. Reviews of all electrical and mechanical designs should be held to make the system electromagnetically compatible. Compatibility and operational requirements must be considered jointly throughout the various stages of design and development.

After operational requirements of the system have been established, a decision must be made as to how these requirements can best be met. A system that is the first choice from the standpoint of operational capability may be a poor choice from the standpoint of EMC, not only from an intrasystem standpoint but also from the consideration of compatibility with environment. Many considerations affect the overall analysis.

The relationship between basic elements of the problem are complex and difficult to define precisely. One of these elements is spectrum occupancy. Consultation with the spectrum management group should be an early step.

EMC PROBLEMS DURING DEVELOPMENT

After methods for meeting operational requirements have been established, technical parameters are examined. Technical parameters can be divided into two basic types: design parameters such as power output, operating frequency, modulation, rise time, and output impedance; and interference parameters such as spurious outputs, spurious responses, susceptibility levels, and transient level.

The methods of meeting technical parameters are straightforward if there are no constraints on certain physical parameters and others. Constraints on an airborne weapon system may take the form of limits on cost, weight, and size. Reliability and maintainability requirements are always of prime importance, and the time schedule and economic factors must be considered.

Usually trade-offs must be made. For example, an EMC power line filter that will meet reliability requirements may exceed weight and size limitations. A compromise must be made that will not degrade performance unduly. As another example, the access cover on a shielded cabinet may require 20 machine screws for a closure that will not impair the shielding effectiveness of the cabinet. Maintainability requires that this cover be removable in 30 seconds. Compromise for this dilemma may require a complete mechanical redesign. Another example might involve the time schedule. Sometimes the contractor may take on a development program with a time deadline. If this involves the development of a jammer transmitter of a certain power level that is pushing the state of the art, the customer will have to decide whether to hold to his time schedule and settle for less power output or extend the contract deadline with the hope of achieving a more desirable power output level.

Trade-offs often are more complex than the examples above, and one may involve all of the factors of cost, weight, size, reliability, maintainability, and time.

EMC PROBLEMS IN PRELIMINARY AND BIS TRIALS

A well-managed EMCP should have only very few, minor EMC problems in the final product. Problems that show up during preliminary trials are often due to various types of coupling: wiring and cabling, shield leakage, ground path coupling, and radiated signal coupling. The reason for this is that while each component and each subsystem can be checked out on the test bench, when they are put in place in the airframe the coupling paths may exceed original estimates made in design stages. The solution usually lies with rearrangement of cabling and wiring and possibly the addition of filters or the upgrading of existing filters. Improvements in shielding are not so easily taken care of and may require considerable reworking. Coupling in the ground system is not hard to fix but it is often difficult to isolate the trouble area. Radiated signal coupling may require relocation of antennas or adjustment of antennas to reduce side lobe or back lobe patterns.

When the aircraft enters the Board of Inspection and Survey (BIS) trial, it has been checked out thoroughly by the contractor. EMC problems that show up at this point are either a result of a difference of interpretation of test results or are minor problems that require evaluation of the degree to which they degrade performance.

EMC OPERATIONAL PROBLEMS AND THE USE OF RETROFIT

When EMC problems appear in service, they are operational problems and are handled in the regular maintenance routine if possible. Problems that cannot be handled in routine maintenance may use any one of the following services:

(1) On-site engineering consultation
(2) Assistance in prototyping special installations, mock-ups, or changes
(3) Review and evaluation of changes and modifications proposed by maintenance activity.
(4) Assistance in preparation of proposed changes or bulletins

These operational problems may be the result of operation in an unforeseen environment. This would not necessarily be an EM environment but might be the result of the interaction of temperature, humidity, and other factors on sensitive electronic parts.

When the cause of trouble and the method of fixing have been established, tried, and tested, the change that will cure this problem should be incorporated in all future production of the weapon system. It may also be desirable to make this same change in all aircraft weapon systems of this type that are in the field. A retrofit program takes care of this requirement.

REVIEW OF FAILURE REPORTS - 3M SYSTEM

The Navy Maintenance and Material Management (3M) System has two distinct parts: the Planned Maintenance System (PMS) in which the technician carries out preventive maintenance according to the instructions on individual Maintenance Requirement Cards (MRC) covering each piece of equipment; and the Maintenance Data Collection System (MDCS) through which the technician reports the problem he encounters in his corrective maintenance, the steps he takes toward their solution, and any need for further action which is beyond his capability at the time.

Forms required in the MDCS are the Shipboard Maintenance Action (SMA) and the Deferred Action (DFA) forms, applicable to work performed on site by which equipment can be evaluated; and the Planned Maintenance System Feedback Report, OPNAV Form 4700/7, by which the PMS itself can be updated for greater efficiency.

EMC ENVIRONMENTAL CONDITIONS

Technological design of an aircraft must include consideration of the environment in which the aircraft will be deployed. From the EMC viewpoint, this requires that aircraft systems be designed to be compatible with other services and activities that share the electromagnetic spectrum. The aircraft must be designed to share, without suffering or causing degradation of performance below specified limits, an environment that contains the electromagnetic devices of other aircraft, ships, and facilities.

SPECTRUM ENGINEERING

The electromagnetic spectrum is occupied by a large number of claimants, each of whom feels that his needs are paramount. Without orderly spectrum engineering and management, conditions would rapidly degenerate into chaos. Compatible use of the spectrum requires each occupant to exercise restraints and to meet certain responsibilities. Basically, this consists of radiating no more functional power than necessary, occupying no more bandwidth than necessary, using no more time than necessary, and keeping spurious emission to a minimum.

FREQUENCY MANAGEMENT

For military systems, frequency management is a responsibility of the Federal Government, affecting all phases of systems development, design, test, evaluation, and operation. The earliest stages of planning should include plans for fitting frequencies used by the new system into the spectrum. To provide for

effective evaluation of the compatibility of system components, and to prevent expenditures for system components that lack frequency allocations, DD Form 1494, "Application for Frequency Allocation," should be prepared and submitted as part of the planning for each component of the system that requires a frequency allocation. A frequency assignment should be obtained from the Chief of Naval Operations through the cognizant Naval Systems Command for each proposed transmitting or receiving component of a system before the design proceeds into the initial development stage and at any time in later development stages when a change in frequency is contemplated. Each military department has certain frequency channels from which it can make assignments directly. Controversial or conflicting assignments are referred to higher echelons: to the DoD Joint Frequency Panel for interservice considerations, then to the Office of Telecommunication Policy, and if necessary, to the President of the United States.

USE OF SPECTRUM ENGINEERING FACILITIES

In the Tentative Specific Operational Requirement (TSOR) phase of system development, a feasibility study is performed to evaluate the proposed electromagnetic characteristics of the system. Central EMC data files are maintained by ECAC, with additional facilities available from Area Frequency Coordinators and the systems command concerned.

Once a frequency assignment is obtained in which frequency, bandwidth, and power output are specified, hardware design can proceed in compliance with these parameters. Deviation from original tentative requirements calls for a new frequency assignment and a new evaluation. Frequency assignments for military systems are Government responsibility, and a military representative must be in charge of on-the-air testing. ECAC should be informed of test results of final configurations so the information can be used in planning subsequent systems.

OPERATION AND MAINTENANCE CONSIDERATIONS

Operational requirements of a combat aircraft include being able to navigate to the target, deliver weapons effectively, and return to base without the mission being degraded below acceptable limits by EMC requirements. Calculated needs of the system to achieve electromagentic compatibility are built into the aircraft as part of the design. Design discrepancies may be discovered during operation and maintenance that require further action to achieve a suitable degree of electromagnetic compatibility.

Organizational contributions to operational compatibility call for selecting operating frequencies, planning mission profiles, and briefing flight crews on

tactics and procedures that have been evaluated from the EMC viewpoint. Flight crew contributions to EMC consist of:

(1) Selection of operating modes, operating times, and combinations of equipments for best EMC.

(2) Observing EMC deficiencies, narrowing them to the offending equipment, operating mode or procedure as far as possible, and reporting findings to the appropriate authority.

Maintenance to EMC standards does not currently follow the usual shop or flight line procedures. EMC maintenance must consider the aircraft as a complete system that must function acceptably in an environment that contains a variety of other systems. Normal maintenance is concerned with such things as sensitivity of a receiver or power output of a transmitter. EMC maintenance is concerned with minimizing the effects of one equipment or subassembly upon another, not necessarily within the same aircraft. This may involve determining the degradation of communication receiver sensitivity when a radar is operating, or determining the loss of weapon system accuracy when TACAN is operating, or any of many other possibilities. Technicians not familiar with EMC requirements have been known to peak transmitter power outputs well above recommended or authorized power levels, thus producing intolerable levels of spurious frequency outputs that wreak EMI havoc with surrounding systems. Technicians striving for high receiver sensitivity have also been know to narrow the bandwidth of a receiver by peaking the alignment adjustments rather than following prescribed procedures, thus rendering the receiver more susceptible to post-impulse ringing, stage over-load, and stability problems. Maintenance for communications-electronics equipments is directed primarily toward the functional aspects of the equipment such as the intended emission and intended response, but does not include the nonfunctional aspects such as spurious emissions and responses. At present, Maintenance Requirement Card (MRC) procedures do not include EMC requirements. Until this shortcoming is corrected and appropriate test equipments and test procedures provided, EMC maintenance will depend largely upon ingenuity of maintenance technicians.

FLEET INPUTS TO EMC ADVANCEMENT

Deficiencies in EMC discovered during operation of an aircraft in the Fleet should be evaluated and reported promptly to the Director for Tactical Electromagnetic Programs (OP-93) by the operating organization. Reports from forces in the field are important to improvement of electromagnetic compatibility and are used by several different activities. Reports of weakness in EMC design may lead to preparation and issuance of modifications and retrofits to aircraft in production and operation, as well as to design improvements of aircraft systems in the planning and development stages. Reports of EMC problems relating to frequency management are used by activities engaged in planning and processing data concerning spectrum occupancy.

The Maintenance Data Collection System (MDCS) portion of the Material Maintenance Management Program provides means for operational forces to

report materiel problems, steps taken toward solution, and any need for further action. Because design compatibility problems usually call for a modification rather than repair, the MDCS is useful for calling EMC deficiencies to the attention of the Naval Material Command.

DETECTING, REPORTING, AND RESOLVING EMC DISCREPANCIES

Operational forces are sometimes confronted with EMC problems which, for a number of reasons, were not adequately or finally resolved in the design and test stages. Possible reasons for EMC deficiencies are:

(1) Specifications and standards not adequate for control of the particular problem.
(2) Problem not anticipated in prediction, planning, and analysis.
(3) Design tests and BIS trials inadequate or did not cover the particular problem area.
(4) Production model aircraft or its equippage differs in some respect from test model.
(5) Problem appears only after aircraft has been operating for a certain period of time.
(6) Aircraft mission envelope changed from that originally intended, or growth missions added to mission envelope.
(7) Changes that affect EMC made to aircraft or its equippage.
(8) New systems or equipments added to environment in which aircraft operates.
(9) Greater operational demands placed upon aircraft system performance than allowed for in original EMC specification limits.
(10) EMC control measures degraded through inadequate or improper maintenance.

Operational organizations have become tolerant of EMI because it is always present to some degree. Within practical limits of aircraft design, interference cannot be eliminated entirely. The objectives rather are to keep effects of EMI from degrading system performance below a specified level. To obtain even 3dB improvement may exact a weight and complexity penalty not commensurate with the rewards. Operating forces should therefore recognize incompatibilities as EMC discrepancies that impair the performance of a mission, or are a hazard to flight safety.

Detecting an EMC problem is a fairly simple matter if, for example, the radar creates severe audio disturbance in the aircraft IC system, or if keying the HF transmitter causes the pilot's seat to eject through the canopy. There are many clues to the presence of EMI, some of which require more perception than others. Typical indications are:

(1) Characteristic sounds in various circuits of the IC system.
(2) Various panel indicators give erratic or erroneous values when certain equipments or combinations of equipments are turned on or radiated.
(3) Various panel warning lights come on at the wrong time or fail to come on when they should.

(4) Visual indications of EMI degrade radar, ECM, and Direct Readout Vertical Indicator (DRVI) scope displays.
(5) Flight stabilization, autopilot, or control booster systems disturbed when an equipment is turned on or a transmitter radiated.
(6) Automatic ECM or target acquisition systems indicate targets when none are present, or fail to recognize existing targets.
(7) Target tracking symbols unstable in electronic weapon sights or Direct Readout Vertical Indicator (DRVI) scope.

EMI can produce many other effects, some of which are not obvious. Operation and maintenance personnel should be alert to detect symptoms of EMC deficiencies, to determine if capability is degraded below acceptable limits, and to isolate the cause to a particular equipment, combination of equipments, frequency channel, or operating mode.

If the findings show the problem to be a weakness in design, this should be reported by the most direct means to the cognizant office of the Naval Material Command. The Naval Material Command, on being advised of the problem, has recourse to several courses of action. An EMC field team may conduct further investigation of the problem, the problem may be corrected at a rework facility, a modification may be issued to operational organizations, or a retrofit may be made.

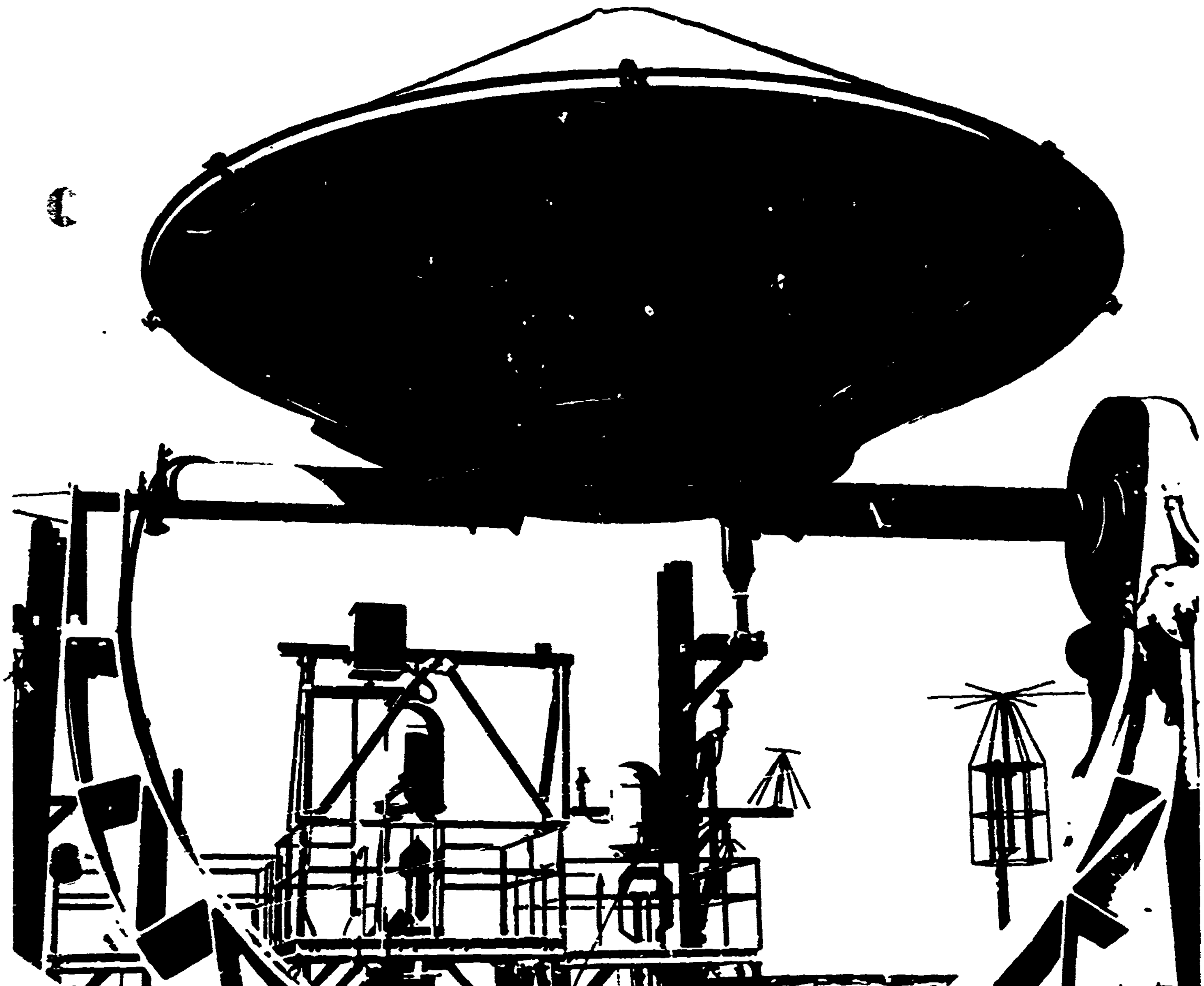
Problems not caused by design deficiencies should be acted upon by operating forces. Frequency assignment problems should be resolved at the lowest level of command having control of the assignments involved. Problems relating to maintenance, such as improperly installed bonds, damaged RF gaskets, wrong MIL-SPEC electronic parts, or equipment adjustment procedures can be handled through organizational maintenance and supply activities.

NAVAIR 5335

NAVAL AIR SYSTEMS COMMAND

ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 9



PUBLISHED BY DIRECTION OF COMMANDER, NAVAL AIR SYSTEMS COMMAND

CHAPTER 9
MANAGEMENT FOR EMC CONTROL

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REQUIREMENTS OF GOVERNMENT AND INDUSTRY

Goal of the joint EMC effort of Navy and industry is to produce weapon systems that will operate as intended within their operational environments. The increasing complexity of weapon systems has created stringent demands on both Navy and industry to implement a sound Electromagnetic Compatibility Program.

Basic administrative and technical guidelines must be established to assure satisfactory implementation and control of efforts toward achievement of electromagnetic compatibility in systems that employ C-E devices. These guidelines must describe in detail the nature and magnitude of the EMC effort, the EMC responsibilities of contractor and government organizations, the methods to be used to achieve administrative and technical control of the EMC program, and the program scheduling and reporting milestones to be used.

The three EMC program implementation and control documents commonly required by contract are outlined in MIL-E-6051D. They are:

1. The Electromagnetic Compatibility Control Plan
2. The Electromagnetic Compatibility Test Plan
3. The Electromagnetic Compatibility Test Reports

The Electromagnetic Compatibility Control Plan for implementation of the system EMC program defines the program management controls. It specifies the engineering design criteria, the subcontractor control, and the test techniques used to determine conformance with standards and specifications that will enable the system or subsystem to perform its intended functions without suffering or causing interference. The Electromagnetic Compatibility Control Plan must be reviewed and approved by the procuring agency before it is officially implemented. When so approved and implemented, it becomes part of the contract requirements.

To formulate and implement the provisions of the Electromagnetic Compatibility Control Plan, the prime or integration contractor may be required by contract to establish an Electromagnetic Compatibility Advisory Board (EMCAB) to assist in an advisory capacity, the contractor and subcontractor organizations concerned with electromagnetic compatibility of systems and subsystems.

The EMC Test Plan details implementation and application of the test procedures used to verify compliance with MIL-E-6051D. The EMC Test Plan, as well as the EMC Control Plan, is prepared by the prime contractor and represents a plan for formal demonstration of system or subsystem electromagnetic compatibility. Test procedures should be well defined to ensure the integrity of the test results.

The EMC Test Report is a formal report of the EMC Test Plan findings prepared in accordance with MIL-STD-831. If technical support data required for the EMC Test Report is published in other documents required by the contract, such as the EMC Test Plan, it may be included in the EMC Test Report by reference. The format of the test report is specified in MIL-STD-831.

APPLICABLE DIRECTIVES

The Department of Defense Directive 3222.3 of 5 July 1967 established an integrated Electromagnetic Compatibility Program within the Department of Defense. This directive governs compatibility requirements of all military equipment from conceptual through operational phases. It assigns specific or joint responsibilities to the Secretaries of the Navy, Army, and Air Force (Figure 9-1). Implementation of the DoD Directive within the Department of the Navy is shown in Figure 9-2.

The DoD directive and ensuing Navy instructions reflect DoD and Navy philosophy for developing an organized EMC Program. It is industry's responsibility to respond to this philosophy by establishing an EMC Program to fulfill the EMC requirements imposed on the weapon system. Requirements are documented in military specifications, standards, or Navair requirements, (AR's) or a combination of all three. The initial response of industry to Navy EMC requirements is the decision of management to accept responsibility for establishing an effective EMC Program.

SPECIFICATION INTERPRETATION AND APPLICATION

In managing and implementing the system EMC Program, the controlling specifications must be interpreted and applied to fulfill the requirements of the contract.

The most widely invoked system EMC specification is MIL-E-6051D, "Military Specification, Electromagnetic Compatibility Requirements, Systems." MIL-E-6051D outlines overall requirements for systems EMC, including control of electromagnetic environment, lightning protection, bonding, grounding, and static electrification. This specification is applicable to systems and all associated subsystems.

It should be clearly stated that fulfilling systems level EMC requirements of MIL-E-6051D is the ultimate goal of all other EMC specifications and standards such as MIL-STD-461A, MIL-STD-462, MIL-STD-469, MIL-B-5087B and MIL-W-5088C. The EMC Control Plan should also state the manner in which the invoked standards are to be augmented or tailored to achieve compatibility of the system elements.

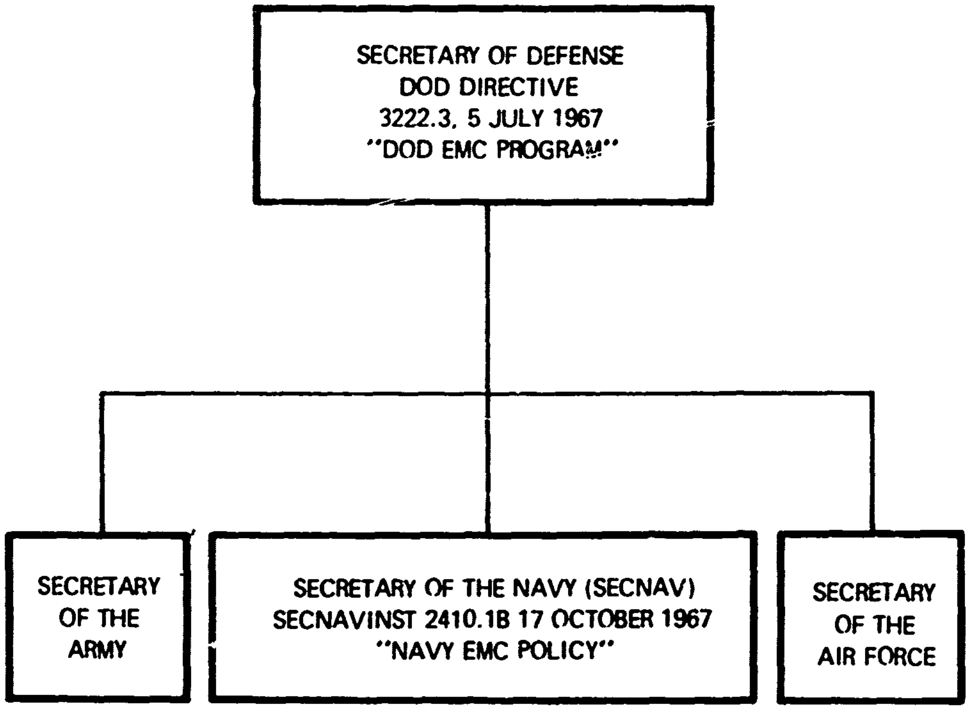


FIGURE 9-1 DOD ASSIGNMENT OF EMC RESPONSIBILITY

MIL-E-6051D outlines overall requirements for systems electromagnetic compatibility programs, including the Electromagnetic Compatibility Board, Systems Requirements, Control Plan, commercial subsystems/equipment, government furnished equipment, subsystems equipment installations, and redesign of systems.

MIL-E-6051D requires the prime contractor to establish an overall integrated compatibility program for most system development or procurement projects. The EMC Program should include the prime contractor's approach, planning, technical criteria, and management control based on the governing documents. It also states that vendors, subcontractors, etc. involved in the program shall establish the same criteria as the prime contractor in accomplishing their EMC Program.

MIL-E-6051D requires that an EMCAB be established to act in an advisory capacity to the system EMC Program, provide means of solving problems, expedite solutions, and establish channels of coordination. The membership and proposed charter are included in the prime contractor's EMC Control Plan. AR-43, "Electromagnetic Compatibility Advisory Board, Requirements for" covers general requirements for the formation and operation of an EMCAB on any Naval Air Systems Command contract that has an EMC Program. The document is intended to establish the general framework within which an

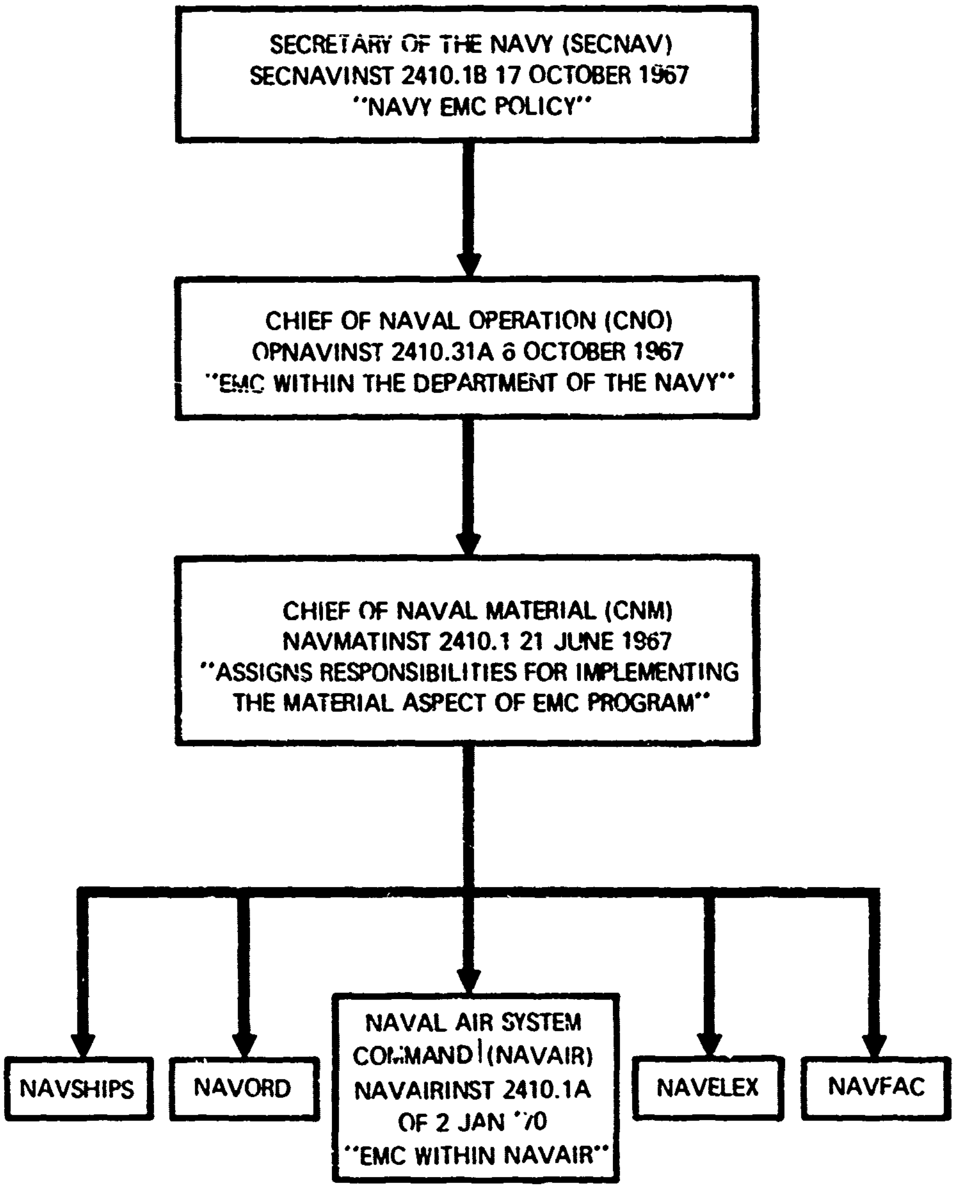


FIGURE 9-2 NAVY ASSIGNMENT OF EMC RESPONSIBILITY

EMCAB can be organized and operated. The following tasks are assigned to the EMCAB:

1. Group discussions to reveal potential problem areas
2. Review of the EMC Program
3. Examination of potential problem areas
4. Defining specific problems

5. Determination of possible problem solutions
6. Selection of the most desirable solutions
7. Recommendations to the performing activity
8. Review of the results of the recommended solutions

Documents Applicable to MIL-E-6051D

Section Two of MIL-E-6051D, "Applicable Documents," refers to other specifications, standards and manuals that form an integral part of the standard. The reference specifications, with the exception of MIL-B-5087 and MIL-P-24014, are documents covering capacitors and filters. EMC Program management should ensure that the contractor's Purchasing Group is cognizant of these specifications when ordering these components. The Design Engineering Group and Quality Assurance Groups should also be aware of these specifications when ordering components and determining equipment reliability.

MIL-B-5087, "Bonding, Electrical and Lightning Protection for Aerospace Systems," is discussed in detail in Chapter 11. The requirements of this specification should be used by the design group through final fabrication.

MIL-P-24014, "Preclusion of Hazards from Electromagnetic Radiation to Ordnance, General Requirements for," established general requirements for weapon systems to preclude hazards from electromagnetic fields to ordnance systems. This requirement applies to all Navy systems in which safety and emergency devices and auxiliary equipment containing electrically initiated explosives or pyrotechnic components are used. Section 3.4, titled, "Susceptibility Control," consists of certain design criteria for the use of Electroexplosive Devices (EED's). Item 3 in the list, "Minimizing Coupling of RF energy from Environmental Fields Into EED's," is covered in detail in Section 3.8 of MIL-E-6051D. Good EMI suppression techniques are of prime importance in this area and this document is normally invoked by the contract.

MIL-STD-454, "Standard General Requirements for Electronic Equipment" lists 63 detail requirements concerned with military specifications for electronic equipment. It promulgates uniform requirements applicable to electronic equipment, with the intent that they be incorporated by reference in general equipment specifications.

MIL-STD-461, "Electromagnetic Interference Characteristics, Requirements for," and MIL-STD-462, "Electromagnetic Interference Characteristics, Measurement of," are documents applicable to components and subsystems as MIL-I-6051D applies to systems.

MIL-D-8706B (AS), "Contract Requirements for Aircraft Weapons Systems," paragraph 3.5.22 (26) invokes bonding specification MIL-B-5087 and requires that a report of resistance measurements of such bonds be made. Paragraphs 3.6.5 (10) and (11) of MIL-D-8706B (AS) also call for interference and compatibility tests and reports on electrical and electronic systems.

MIL-D-8708B(AS), "Demonstration Requirements for Airplanes," calls for flight and ground tests to demonstrate the performance and compatibility of the avionic systems under conditions simulating to the mission of the aircraft. It also

requires submission of an Avionics System Demonstration Data Report, which includes test data regarding electromagnetic compatibility and interference characteristics of the system.

Other pertinent reference documents are:

1. MIL-STD-704, Electrical Power, Aircraft Characteristics and Utilization
2. MIL-STD-831, Test Reports, Preparation of
3. MIL-STD-2584, Plug, Fuel Nozzle, Grounding
4. MIL-STD-33645, Receptacle Installations, Fuel Nozzle Jumper, Aircraft to Servicing Hose
5. MIL-STD-90298, Connectors, Receptacle, Electrical Fuel Nozzle Jumper Plug
6. Air Force Manual AFSM 80-7, Handbook of Instructions for Aerospace Vehicle Equipment Design
7. Air Force Manual AFSM 80-9, Vol. IV, Electromagnetic Compatibility

In addition to citing EMC specifications and standards, the system EMC Control Plan should include all requirements necessary for an adequate EMC Program although they may not be stated in the specifications and standards. These extra requirements should receive particular attention, and the applicable specifications and standards themselves often require extensive interpretation to fit the particular procurement. Typical of some of the extra requirements that should be presented are:

1. Transient susceptibility testing of equipments and subsystems
2. Audio frequency susceptibility over the range of 15 to 150 kHz for equipments and subsystems
3. EMI emission or susceptibility of interface, ancillary, or interconnection devices that may not appear in equipment or subsystem requirement lists
4. Direct current resistance measurements with an approximate limit of 0.0025 ohm to assure a continuous ground reference plan
5. Susceptibility testing of equipments to determine the threshold of susceptibility. This will require a higher signal level than the 100,000 microvolts generally used
6. Visual inspection of grounding techniques to assure that there is an adequate radio-frequency grounding system
7. Initial systems level EMC testing performed on individual subsystems to define a data base for subsequent system level tests, familiarization with EMC monitoring equipment, and familiarization with the operation of the system

ELECTROMAGENTIC COMPATIBILITY ADVISORY BOARD

The prime or integration contractor designated in the procurement contract may be required by certain contracts to establish an Electromagnetic Compatibility Advisory Board (EMCAB) to provide assistance in an advisory capacity on matters relating to EMC. Detailed requirements for the EMCAB are set forth in NAVAIR Requirement AR-43, "Requirements for Electromagnetic Compatibility Advisory Board."

Formation of EMCAB

The proposed charter of the EMCAB and details of its operation are included in the Electromagnetic Compatibility Control Plan. Members of the board are typically the contractor, subcontractor, vendor, ECAC, and procuring activity representatives qualified in EMC requirements. Procedures for appointing members are prepared carefully to ensure that each representative has adequate experience and authority to participate in, concur with, and implement board recommendations and agreements.

EMCAB Requirements

In general, the EMCAB assists in implementing the Electromagnetic Compatibility Control Plan, expedites solutions to EMC problems, and establishes high level channels of coordination. The EMCAB works to ensure that each participating associate, subcontractor, and vendor works in accord with the overall program EMC objectives; that effective methods of monitoring EMC efforts and progress are established and followed; that periodic EMC Program design reviews are scheduled; and that deficiencies noted are promptly corrected. It is the responsibility of the EMCAB to review the EMC Program, initiate studies, make recommendations, and otherwise assist in achieving electromagnetic compatibility among similar or dissimilar electrical and avionic systems, subsystems, and equipments.

EMCAB Objectives

The objective of the EMCAB is to assist in resolving EMC problems that arise during the life of the procurement contract by advising the contractor and subcontractors of appropriate methods for correcting EMC deficiencies. The statement of objectives in the EMCAB charter defines this objective and delineates the steps in accomplishing this objective. These steps include such activities as:

1. Group discussion by EMCAB and design personnel to reveal potential problem areas
2. Continuing review and updating of the EMC Program
3. Examination of potential problems and definition of specific problems
4. Determination of possible solutions and selection of the best one
5. Recommendations of corrective measures to the performing activity
6. Review of the effects of the recommended solution

EMC CONTROL PLAN

The Electromagnetic Compatibility Control Plan is a formal document describing a multi-phased EMC Program for predicting, analyzing, monitoring, measuring, and controlling electric and magnetic interference within systems or subsystems.

The final objective of the EMC Control Plan is to confirm by testing that no undesirable response, malfunction, or degradation of performance due to

electromagnetic interference will occur in, or be produced by, electrical or electronic equipment in the aircraft. Maximum feasible system and subsystem operational compatibility and overall weapon system effectiveness, obtained by competent design, are the criteria to be considered in developing the EMC Control Plan.

The importance of the EMC Control Plan cannot be over-emphasized. Simply stated, it describes the entire EMC Program by which all subsequent EMC documentation, requirements, specifications, test methods, and criteria are controlled and enforced. Thus it is obvious that the management requirements, organizational responsibilities, design criteria, test procedures and limits, and related matters must be clearly defined to assure the acceptance or approval of the plan.

If the EMC Program is to be accomplished by a contractor, an enforceable EMC Control Plan is normally assured by making MIL-E-6051D a part of the basic contract. If the program is to be accomplished in-house, a directive from program management stipulating MIL-E-6051D as an applicable document usually assures an enforceable EMC Control Plan, but other approaches may be used.

Following the guidelines presented will help to obtain acceptance or approval of the EMC Control Plan. It is suggested that the plan be presented in sections as follows:

1. Introduction
2. Applicable documents
3. Specification interpretations
4. Program management requirements
5. Design requirements
6. Test requirements
7. Quality assurance tests
8. Definition of terms

A sample EMC Control Plan is included in Appendix A. Reference to the pertinent section of the sample EMC Control Plan will be helpful in following the text.

Introduction to EMC Control Plan

The introduction to the EMC Control Plan should contain a brief statement of the scope and objectives of the plan. It should introduce the system to which the plan is applied, and state the objectives of the plan and the military specification to which it was prepared. The introduction should also stipulate a time for review and updating of the EMC Control Plan. A period of not more than six months is recommended.

Documents Applicable to EMC Control Plan

The list of documents applicable to the EMC Control Plan should include the standards, specifications, drawings, plans, and reports to be used in meeting the requirements of the plan. Applicable EMC documents developed by the

military, the contractor, and vendors should be included. Effective dates of the listed documents and all restrictions or limitations affecting the incorporation of the documents should be included.

Tailoring EMC Specifications to the EMC Program

To validate the EMC control program, the EMC specifications and standards cited must be analyzed for applicability to the total design program. When more than one specification or standard is cited, an order of precedence must be established to resolve conflicts. Requirements developed during the contract definition will probably take precedence over all other military specifications and standards.

Interpretation may be necessary if the specifications are several years old and do not conform to current design requirements. Frequency ranges, test configurations, and other details may not always fit the needs of present systems. Because some specification limits are very severe, their impact on system effectiveness, cost, and weight must be considered.

Interpretation is also required because the specifications have been prepared to apply to conditions in as wide a range as possible. A systems level specification may have been written to apply to any system, from a ground station consisting of one rack equipment to an aircraft containing multiple equipments and subsystems.

Interpretation may also be required if the procurement contract or order is actually reprocurement of an equipment or subsystem designed under a specification now superseded.

Therefore, because of the age and broad scope of the commonly used specifications, interpretation by competent EMC persons is mandatory for each overall program. Within the program, EMC specification analysis and interpretation are the responsibility of one organization; the contractor's EMC organization are assigned this function. The findings and recommendations are reported to the procuring activity, using Specification Analysis Sheet DD Form 1426. (A sample is attached to most military specifications.)

When specifications have been interpreted and their applicability established, the result may be the modification of some requirements and the imposing of other requirements not called for in the specification. The basic requirement is to satisfy the intent of the specification rather than to be dogmatic about compliance with each detailed stipulation. The intent of MIL-E-6051D may be stated as being "to assure that the system is electromagnetically compatible." MIL-STD-461A intent may be stated as being "to assure that the electromagnetic interference and susceptibility characteristics of subsystems or individual equipments fall within specified limits." As such, any interpretation of MIL-E-6051D or MIL-STD-461A should be adequate for accomplishment of these intentions.

EMC Program Management and Enforcement

Management has a key role in the application of EMC control measures.

This role should begin at the inception of the project, whether large or small. If the project is a "designated project," it will have gone through an extensive definition process before reaching the development or production stage. Solutions to EMI problems in any project require not only the development and application of advanced technology, but the highest order of planning and management. Electromagnetic compatibility can be achieved only by a program that covers both technical and economic aspects and assesses all parameters, including time, cost, and performance. The first step in adequate EMI/EMC control is the selection of effective and enforceable compatibility design criteria to apply to the various portions of the program. This is one of the products of the definition or contract negotiation phase, and the contractor's EMC organization should be represented on the negotiating team.

Proper control depends upon the user of the proposed system and on the system's configuration and mission. Certain combinations of equipments, antenna or cable placements, or of missions, may require more stringent enforcement of EMC controls than those invoked by the commonly-cited military standards and specifications. The effectiveness of EMC control therefore depends upon knowledgeable management rather than upon rote following of general-purpose specifications and standards.

Requirements to demonstrate EMC of the system will have been mutually agreed upon in the contract between the purchaser and the supplier or contractor during contract definition or negotiation. It is then up to the contractor to structure the administration of the program or project so that his EMC organization is directly supported by top management. Variations on integration of the EMC organization into the administrative structure can be endless. A simplified structure of a decentralized EMC organization is shown in Figure 9-3.

One of the most important functions of the EMC Control Plan is that of documenting the responsibility and authority of the individuals who will direct and implement the contractor's Electromagnetic Compatibility Program as required by MIL-E-6051D. The success of the EMC Program will rest upon its effective administration.

The management portion of the EMC Control Plan should establish the organization and responsibilities of the contractor's EMC group, stating their functions and objectives. In general, the contractor's EMC group: 1. participates in periodic design reviews, 2. acts in an advisory capacity to the contractor and subcontractors on EMC matters, 3. performs EMC tests, generates recommendations for the solution or further definition of EMC problems uncovered.

To have a final system that is electromagnetically compatible, EMC control must begin with basic design. Therefore, the authority of the EMC organization to interpret and enforce the design and test engineering controls should be stated in the EMC Control Plan. Management of electromagnetic compatibility extends to the standards and specifications imposed contractually on vendors and suppliers of equipments and components.

The effectiveness with which an EMC control program can be implemented

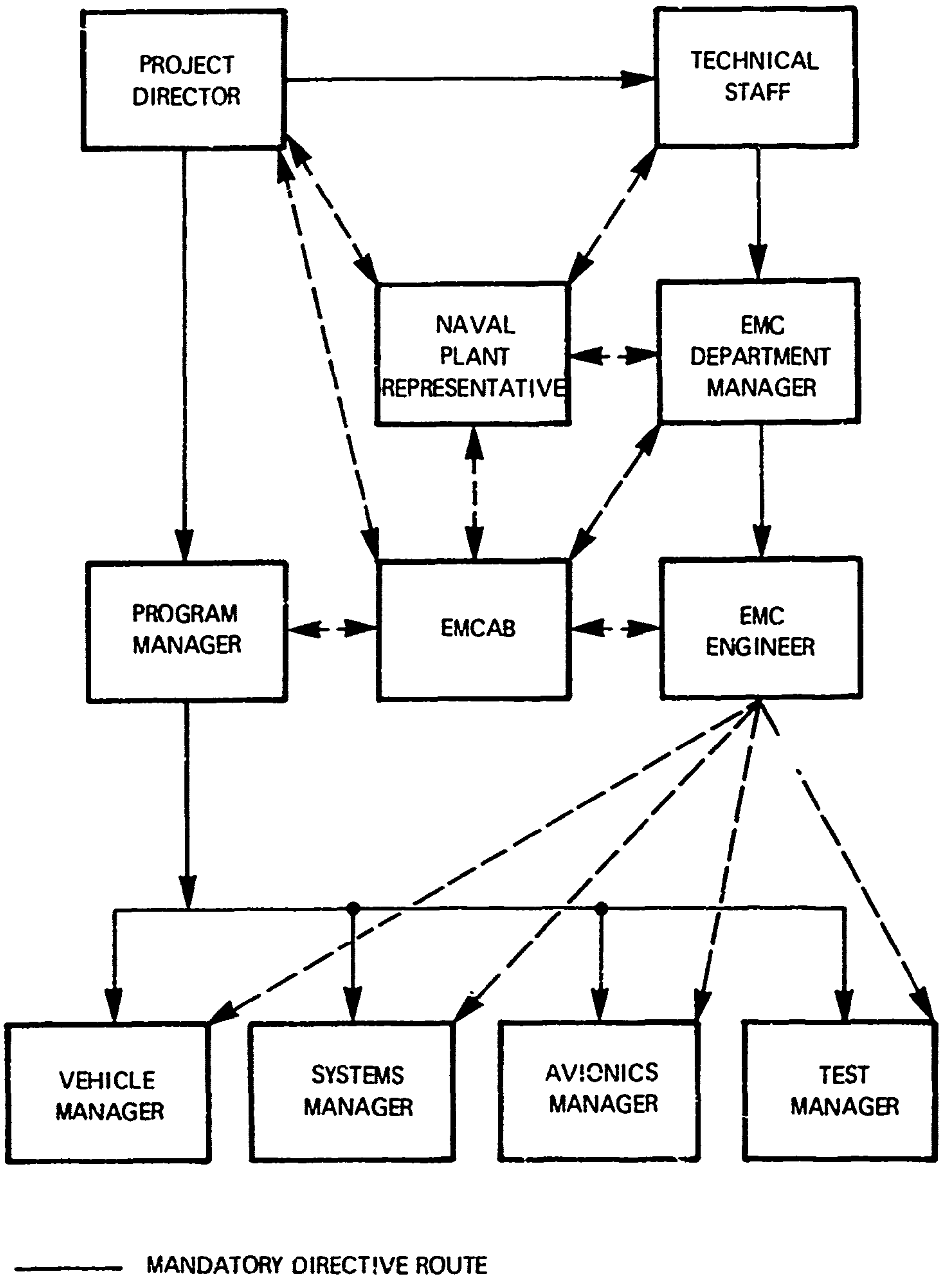


FIGURE 9-3 DECENTRAILIZED EMC ORGANIZATION

is obviously affected by restrictions placed on the program initiators. These restrictions may take the form of time and cost restraints, ineffective organizations, or lack of technical capacities. For these reasons, the EMC Control Plan should contain positive statements of program management's intent to fully support an effective EMC control program, and enough information to assure ready implementation.

In addition to the organizational elements of the EMC Program, the management portion of the EMC Control Plan should specify all EMC documents and reports to be submitted. If the documents are segregated into various levels so that some are submitted to the procuring agency for approval, others for review, and others for general information, this must be shown.

Special attention should be directed to the time between preparation and submission of EMI/EMC documentation. This is particularly important in the case of test results. Within the documentation prepared as a result of the EMC control program, documents that show the status of the EMC efforts in relation to the program milestones should be specifically identified.

The management portion of the EMC Control Plan is monitored by use of the program milestones. These milestones and target dates should be shown in relation to the schedules of the overall program. Typical milestones are shown in Figure 9-4 and should specifically schedule:

1. Preparation and submission of the EMC Control Plan
2. Qualification testing of flight equipment to interference and susceptibility requirements
3. Qualification testing of ground equipment to interference and susceptibility requirements
4. Preparation of the system EMC Test Plan
5. Preparation of the system EMC test procedures
6. Initiation of the electrical/electronic compatibility tests
7. Initiation of the general acceptance test
8. Any other milestones or target dates that the contractor and/or procuring agency consider pertinent.

EMC Design Requirements

The means of assuring satisfactory EMI/EMC design control should be presented in the EMC Control Plan. This includes a statement of the EMI/EMC design guidelines that are to be used, how the design guidelines are to be presented to the design organizations, the controls to assure that the design guidelines are being followed, and the means by which the design organizations are to be informed of the EMI/EMC philosophies of the EMC Control Plan. As a recommendation, EMI/EMC design guidelines should be prepared by one of the responsible contractor organizations. The guidelines should be written to apply to company management as well as to the individual designers. Design organizations should be told of these guidelines in formal training sessions, publications prepared and distributed by the EMC organization, and in conferences of the contractor's EMC group with representatives from all affected organizations.

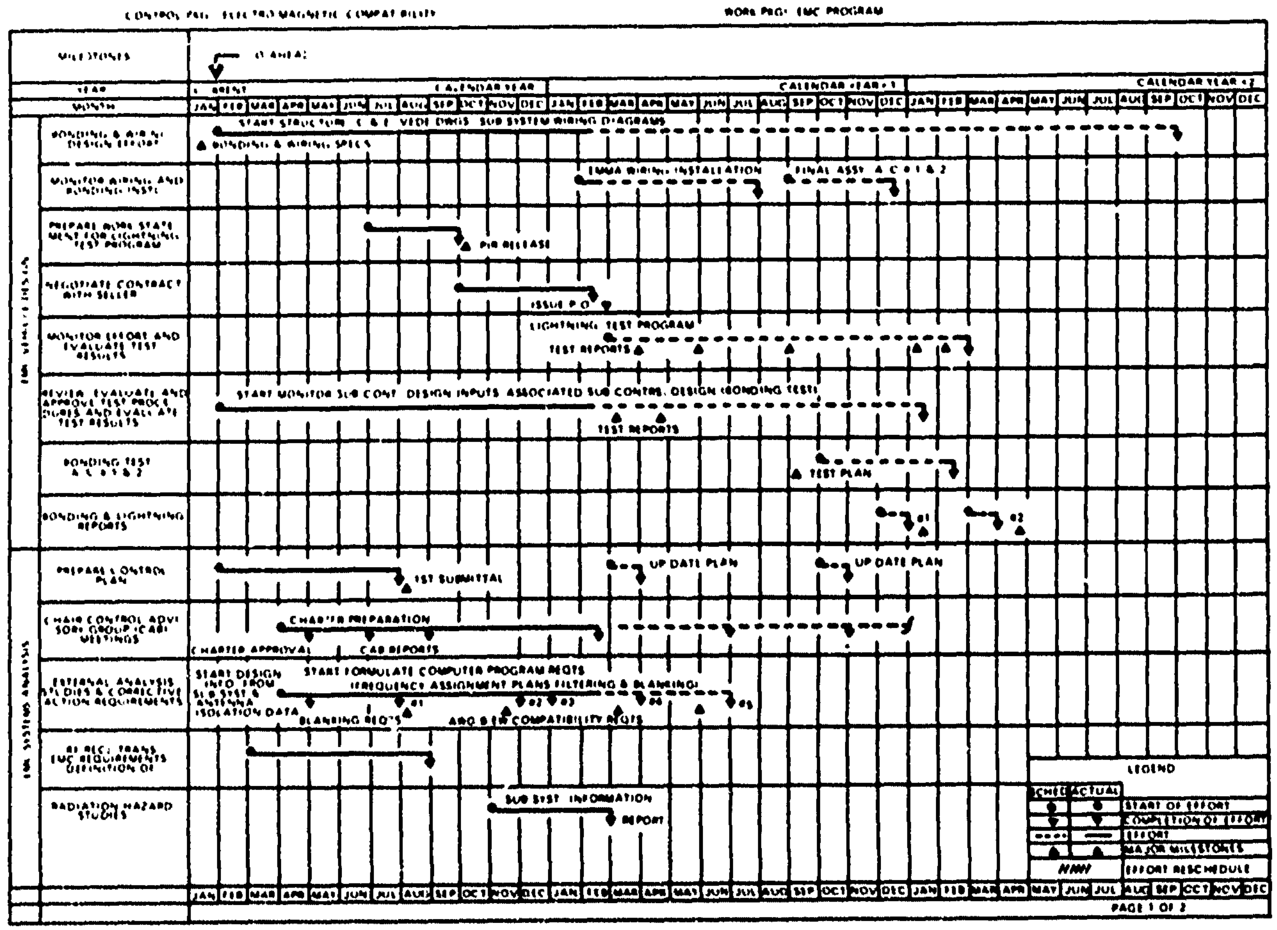


FIGURE 9-4 TYPICAL EMC PROGRAM MILESTONES (PART I)

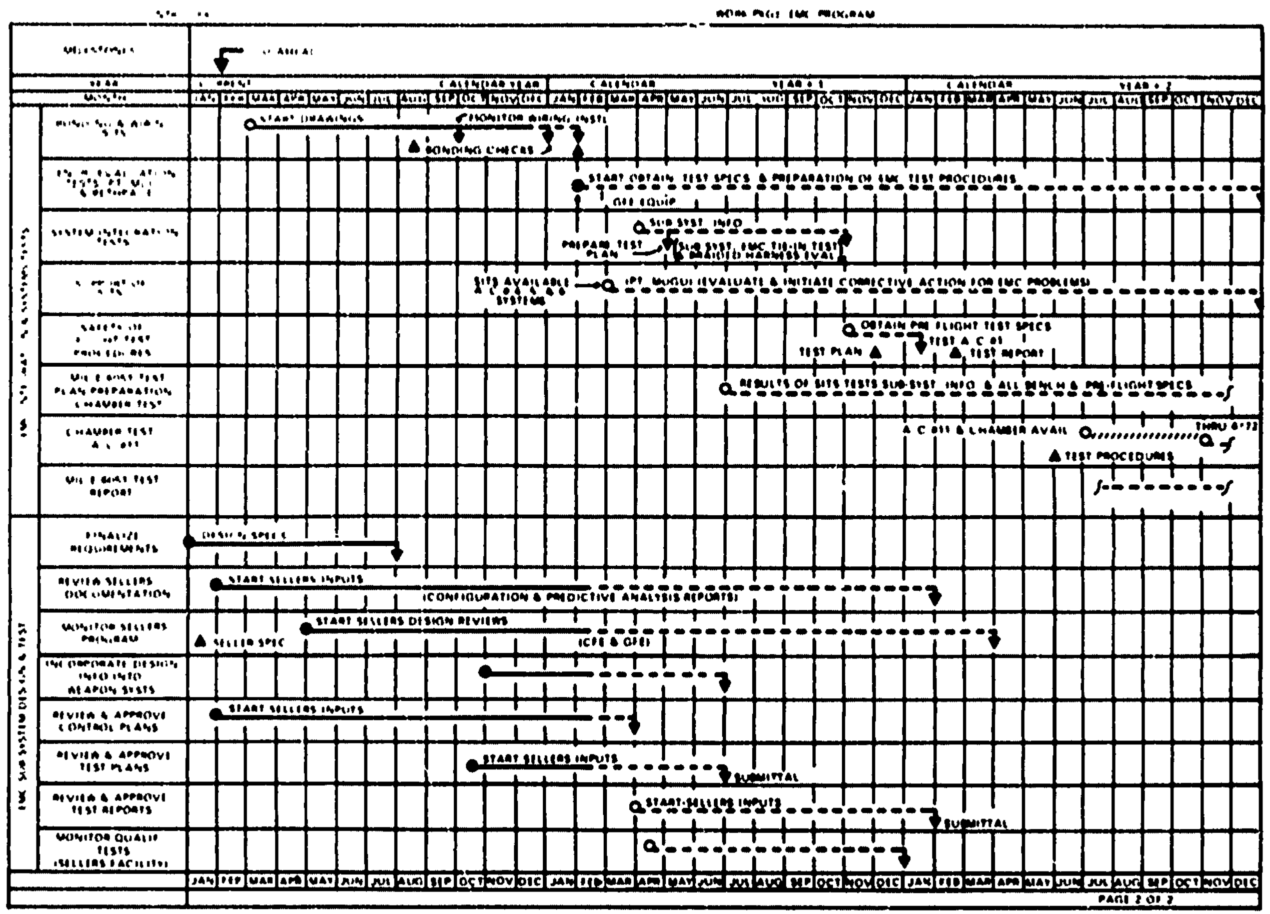


FIGURE 9-4 TYPICAL EMC PROGRAM MILESTONES (PART II)

Subsystem compatibility is to prevail among all subsystems while they are operating individually or collectively. Each subsystem associated with the major system is assigned an EMC criticality category based on the degree of impact that interference or susceptibility may have upon the assigned mission, as follows:

Category I - EMC problems that could result in loss of life or vehicle, aborted mission, costly delays, and unacceptable reduction in systems effectiveness.

Category II - EMC problems that could result in injury, damage to vehicle, or reduction in systems effectiveness.

Category III - EMC problems that result only in annoyance, minor discomfort, or loss of performance that does not decrease desired system performance.

Degradation criteria are established by the contractors of each subsystem and equipment to define its susceptibility. Results of interference tests on the subsystem and equipment can be used to establish susceptibility criteria. Equipment classified as Category I or II may be considered for additional degradation criteria. Justification for an additional safety margin must be considered on systems performance, error budgets, tolerance, repeatibility, and requirements. Further requirements are that existing test points be used, and that use of special equipment manufacturers or circuit breakouts be kept to a minimum. Safety margins less than 6 dB (or 20 dB for explosives) must not be used unless specified in the EMC Control Plan or Range Safety Procedure.

System interference and susceptibility are controlled by adequate design on each equipment associated with the system. This specifically includes operation of equipment using antennas or sensing elements operating in all their modes and performing their intended function. Unless otherwise specified, each equipment shall be designed to meet the requirements of MIL-STD-461A and MIL-STD-462. Due to the severity of some of the imposed limits in MIL-STD-461A and MIL-STD-462, modifications of the limits may be proposed in the Test Plan. Air Force Manual AFSC 80-9, Volume IV, sets forth general design guidance and criteria.

Subsystems and equipments used in aircraft installations must operate without malfunction when supplied with electrical power conforming to MIL-STD-704, including surges, ripple voltages, and other electrical abnormalities.

Bonding and grounding provisions must meet the requirements of MIL-B-5087, MIL-SPEC-90298, MIL-SPEC-533645 and the National Electrical Code USAS CI 1965.

All elements of systems and ground sites must provide adequate lightning protection in accord with MIL-B-5087. Special emphasis and testing are given to ordnance and personnel protection.

System design incorporates provisions for keeping static electricity from degrading system effectiveness. Static dischargers are required as specified by the procuring activity. Conductive coating must be used on all non-metallic material on the external surfaces of the aircraft that are exposed to airflow.

Systems, subsystems, and equipments are designed to protect personnel

from electromagnetic hazards. System design includes provisions to protect ordnance systems, subsystems, and equipments from premature ignition. Good EMI design should be used in laying out wiring, cabling, and hardware associated with the ordnance system, which includes weapons, rockets, explosives, electroexplosive devices, squibs, flares, igniters, explosive bolts, destruct devices, JATO bottles, and similar items.

In system design, the external electromagnetic environment must be considered. Thought must be given to individual mission profiles, available electromagnetic environment data, and the effect of the external environment on system effectiveness.

The purpose of this effort is to assure that every essential EMI/EMC control measure is incorporated as early as possible into equipment design. Otherwise, costly time delays, major redesigns, or serious compromises of equipment operation will result.

In many cases, a subsystem from one organization may ultimately be joined with another subsystem from another organization. The design portions of EMC Control Plans submitted by the two different organizations must present EMC design policy in enough detail to assure the procuring activity that the design of one system will not be violated by the design of an associated system.

Some of the areas for which EMC design specifications must be prepared are:

1. Electrical bonding and grounding: Equipment-to-ground reference plane, electrical interface with other equipments or systems and subsystems, electrical power returns, and conductor shields.

2. Shielding: Equipment and subsystem case shielding, shielding provisions of the system structure, shielding and twisting of conductors, and anticipated electromagnetic and electrostatic environments.

3. Transient control: Suppression of transients from inductive sources, suppression of contactor transients, and surge limiting within the system power profile.

4. Radiated signal control: Spurious signals from intentional radiation sources, unintentional radiation sources, control of response to radiated signals, and projected intentional radiation environment created by the system.

5. Interference and susceptibility prediction: Frequency allocations, antenna locations, antenna patterns, and signal levels.

6. Cable and/or conductor routing consideration: Conductor separation and isolation, and location of equipments and subsystems.

7. Electromagnetic radiation hazard (RADHAZ) and hazards of electromagnetic radiation to ordnance (HERO): Design policy and test procedures to prevent electromagnetic radiation hazard to personnel or harmful operation of weapon systems and electroexplosive devices.

8. Any special EMC considerations: Conditions peculiar to the type of aircraft or to the nature of its intended mission and installed equipments may call for more stringent EMC control or variations to the cited specifications.

EMC Test Requirements

As part of the EMC control program, the contractor is required to present an EMC Test Plan in accordance with paragraph 4.2 of Specification MIL-E-6051D. EMC Test Plan details, together with a discussion of a sample plan, are presented in a following subsection.

Test requirements of the EMC Control Plan should provide for:

1. Preparation of an EMC Test Plan that defines equipment, subsystem, and system level testing to be performed, and that is a contractual requirement over which the procuring activity has approval authority.
2. A statement of criteria used in determining which equipments and subsystems shall be tested.
3. Identification, by nomenclature and serial numbers if possible, of equipments and subsystems to be tested.
4. A statement of criteria used in determining the extent of EMC tests to be performed.
5. A design review to assure that the equipments and subsystems have complied with the applicable design requirements of the EMC Control Plan.

In large companies, many different organizations may be involved in testing equipments, subsystems, and systems to EMC specifications and standards. When this is the case, the EMC Control Plan should indicate the particular tests to be performed by each of the organizations and specify how the results of these tests are to be coordinated from a systems point of view. Active liaison is especially important between testing organizations performing subsystem and equipment tests to MIL-STD-461A and MIL-STD-462 standards, and those performing systems tests to MIL-E-6051D specifications. This is true because the results of the subsystems and equipment level tests are used both to indicate points to be monitored and to establish tolerable limits for the systems level testing.

Active liaison is also necessary when systems level testing is performed at more than one location. In these cases, the test results from one location are used to define test requirements at another location, and the results from tests performed at all locations are combined to show compliance with the applicable systems level specification. Without active liaison between testing efforts, EMC tests are duplicated, excessive time is consumed in performance of EMC tests, and test results lack validity because tolerance limits cannot be established.

Quality Assurance Criteria

Once the efficiency of the EMC control measures has been proved by detailed tests on a test model of the system or subsystem, a simplified test procedure will assure continued quality in production models. It is therefore required by MIL-E-6051D that each production model be given a general acceptance test to ensure compliance with EMC requirements. This portion of the EMC Control Plan sets forth the responsibility for the test and directs attention to applicable portions of the EMC Test Plan.

Other Information Considered Pertinent

Additional information normally included in the EMC Control Plan includes definitions of terms used, methods to be used in the education of design, management, and test personnel to EMC awareness, system quality assurance and production control, or any studies that will be initiated for improvement of the EMC control program.

The definitions portion of the EMC Control Plan is a small part of the total volume, but it is implicitly necessary to establish the extent and scope of the EMC effort. Words and phrases have various meanings to different persons. Some common terms that often are not assigned exact meanings, and therefore require precise definition, are: engineering tests, acceptance tests, ground, interference, susceptibility, ambient environment, compatibility, safety margin, and other such general, non-specific terms.

The EMC Control Plan outline and content described in this chapter is a systems plan in accordance with the requirements of MIL-E-6051D. For individual equipments or subsystems, a separate EMC Control Plan may be required describing the engineering design procedures and techniques complying with equipment standards MIL-STD-461A, 462 and 469. It is desirable that these control plans be separate sections of a single document. The emphasis of the equipment control plan is on equipment design practices, procedures, and guidelines.

All the information stipulated for inclusion in the EMC Control Plan may not be available by the submission date specified in the contract. The rest of the information will become known as the program progresses. Therefore, the EMC Control Plan must be reviewed periodically and updated as necessary. The EMC Advisory Board should logically assist in this updating. The suggested period for review is semi-annually. Even if no updating is necessary every six months, the review will benefit all concerned as a reminder of basic requirements of the EMC Control Plan. The EMC Control Plan is kept updated by the use of supplements or revised pages as specified by the contract.

Example of an EMC Control Plan

The sample EMC Control Plan shown in Appendix A illustrates plan format and typical areas of concern in an aircraft system. Basic requirements for EMC control plans, as set forth in military specifications, must be in a general form to allow the necessary flexibility. This permits EMC Control Plans to be formulated according to the specific requirements of the system. A sample EMC Control Plan tailored to a contract for equipment is shown in Appendix B.

EMC TEST PLAN

The electromagnetic compatibility test program is developed and prepared by the contractor in compliance with MIL-E-6051D requirements. The test plan description in MIL-E-6051D will aid contractors in the preparation of plans to be submitted to the procuring agency for approval.

Because the EMC Test Plan will be reviewed by the procuring activity for coverage of items called for in the military specifications, both the contractor and the reviewer should benefit from the guidelines presented here.

MIL-E-6051D requires that a system electromagnetic compatibility test plan be submitted to the procuring activity as specified in the procurement contract. Requirements for the preparation of equipment test procedures are given in MIL-D-18300. The test plan should be approved by the procuring activity before the starting date of the electrical-electronic compatibility tests. The testing organization is responsible for implementing the intent of the specification. Because the specification requirements in MIL-E-6051D are general in nature, the detailed EMC Test Plan is intended to provide the procuring activity with specific techniques by which the contractor proposes to assure compliance. The specific techniques should be detailed enough so that the procuring activity can duplicate the proposed methods in the laboratory.

The contractor is responsible for preparation and implementation of a system EMC test program in accordance with MIL-E-6051D. The test program must be documented in an EMC Test Plan and submitted to the procuring activity for approval before it is used for EMC tests.

All outstanding engineering documents involving a change to the system must be considered before final approval of the test program. Any exceptions must be approved and must identify the portion of the system that is not of flight or production configuration.

All equipments must have been qualified in accordance with MIL-STD-461, MIL-STD-462, and any additional requirements cited in the system EMC Control Plan.

The system will be operated within the limits of the subsystem or equipment specifications for a maximum indication of interference. Evaluation of system operation and demonstration of applicable safety margins will be monitored by appropriate means on each subsystem or equipment. Instrumentation is as specified in the EMC Test Plan. Because test equipment may become inoperative or unavailable, it is recommended that alternatives be specified in the EMC Test Plan. Special instrumentation can be used with prior approval.

Means of simulating special inputs such as doppler and temperature must be described in the EMC Test Plan.

The EMC tests demonstrate compatibility when the systems, subsystems or equipments are operated individually or collectively in all modes of operation. Transmitters and receivers are to operate at critical frequencies identified during system analysis and subsystem/equipment laboratory test. Transmitter frequencies are chosen so that spurious outputs fall on critical receiver susceptible frequencies.

Voltage transients at the electrical power input of Category I and II type subsystems and equipments (see section entitled "EMC Test Plan") shall not exceed the levels stated. Special equipment and/or transient detectors will monitor these points.

When safety margins have been established and approved, the inputs,

outputs, or other test points will be monitored continuously.

Approved support equipment intended for use with the system will be used to monitor and provide data records. All records will have time and event correlation.

Electromagnetic environment at the test site must be acceptable to the procuring activity before the tests can be conducted. The ambient electromagnetic environment will be monitored continuously in the frequency range from 10 kHz to 20 GHz, except that, by special agreement of the procuring activity, the frequency spectrum may be limited to the areas of susceptibility of the receivers of the system. The test site ambient level must be analyzed, or controlled so that it does not degrade the results. All support or site equipments that are sources of interference will be suppressed, removed, or not operated.

A complete test report, in accordance with MIL-STD-831, describing and annotating the test results, will be provided as required by the contract. A detailed discussion of a test report appears in the section entitled "EMC Test Reports."

Objectives and Compliance Philosophy

A section of the EMC Test Plan should be set apart to state the basic objectives of the test. Compliance philosophy is a part of the objectives and should be treated in broad terms in this same section. As an example, one objective would be to verify by testing that no other onboard system is degraded or inadvertently put into operation. Compliance might be verified by specifying a maximum allowable degradation.

The objectives of the EMC test program are to demonstrate and evaluate compliance with the EMC program. Evaluation of the EMC test program is based on the EMC requirements of the mission profile. It is the laboratory validation of the total electronic design effort.

Test Requirements

Normally, testing for overall compliance includes several discrete tests. Each of the partial tests that make up the overall test should be described in general terms. A test, such as RF radiation compatibility, should be described in scope, operating conditions, and general techniques. A minimum description of the physical aspects of the test effort should include:

1. Selection of critical circuits to be monitored for compliance with degradation criteria and safety margins
2. Procedures for developing failure criteria and limits
3. Test conditions and procedures for all electronic and electrical equipment installed in or associated with the system, and the sequence for operations during tests, including switching
4. Implementation and application of test procedures that include modes of operation and monitoring points for each subsystem and equipment

5. Use of approved results from laboratory interference tests on subsystems and equipments

6. Flight test program (manned systems only)

7. Methods and procedures for data readout and analysis

8. Means of testing design adequacy of vehicle electrification (static electricity) and lightning protection

9. Means of simulating and testing electroexplosive subsystems and devices

10. Demonstration of the approved safety margin for electroexplosive devices, and for systems whose degradation affects safety of flight or mission success

11. Electrical power voltage limits, and methods for monitoring AC and DC power buses to assure that voltages are within the proper limits.

12. Test locations and descriptions of arrangements for simulating operational performance in cases where actual operation is impractical

13. Adjustments and settings of variable controls such as audio gain, video gain, sensitivity, and squelch

14. Details concerning frequency ranges, channels, and combinations to be specifically tested such as image frequencies, intermediate frequencies, local oscillator and transmitter fundamental and harmonically related frequencies. Subsystem susceptibility frequencies identified during laboratory testing shall be included

15. Personnel required: government, contractor, and vendor

16. Calibration schedules and description of unique EMC instrumentation for measuring electrical, video, and mechanical outputs of equipments and subsystems to be monitored during the testing, including applicable safety margins

17. Means of simulating signal inputs such as doppler and radar altimeter

18. Evaluation and degradation criteria for each subsystem and equipment

The EMC test program consists of the system EMC tasks and the subsystem/equipment EMC tasks. System tasks include integration tests, preparation of a test plan, and formal qualification tests with evaluation, recommendations, and retesting as required. Subsystem/equipment tasks include preparation of the test plans, performance of qualification test, evaluation, recommendations, fixes, and retest.

The EMC test program is documented in the system EMC Test Plan, which outlines the contractor proposed method complying with MIL-E-6051D. Submission of the Test Plan to the procuring activity for review and approval permits defining compatible system operation. EMC Test Plans outline methods of qualifying the subsystems/equipment to the requirements of MIL-STD-461 and MIL-STD-462. They depict test conditions, test methods, susceptibility criteria, methods of monitoring, and necessary information peculiar to the subsystem/equipment being tested.

Integration testing is performed to determine the compatibility of groups of subsystems assembled and operated together. These tests are normally performed in the laboratory. In this way, interface problems are resolved before

installation of systems into the airframe. EMC engineers find that certain laboratory mockup tests are invaluable. If there is a system incompatibility, additional isolation such as shielding, filtering, or bonding modifications can be made to the mockup to achieve the optimum problem solution.

EMC systems tests are performed first to verify that the aircraft mission envelope is not degraded by electromagnetic incompatibilities; and second to comply with the procuring activity specifications. The present governing military specification, MIL-E-6051D, imposes four types of EMC tests: 1. functional tests on a complete weapon system, 2. specification compliance EMC tests on the complete aircraft that is fully production configured, 3. EMC quality assurance tests on each final production item on a sample basis and 4. tests on each significant modification or new configuration of equipment or aircraft.

Subsystem/equipment EMC qualification tests are performed by the contractor and/or a subcontractor to demonstrate conformance to limits of MIL-STD-461, and tested in accordance with the test methods of MIL-STD-462. The tests are governed by the subsystem/equipment EMC Test Plan. Formal qualification tests are usually witnessed by the procuring activity to ensure the test validity and the test procedures conform to the approved Test Plan.

Informal EMC evaluation tests are performed to detect any problem before formal test. They are usually requested by either the design engineer during the breadboard stage, or by the EMC engineer during any phase.

Test procedures are documented for in-house use only, although a copy of procedures is usually included in the Test Plan or as an appendix to the test report. The test procedures describe step-by-step, tests on the items under examination and lists the test equipment used for measuring or generating the required EMI data. The results of these tests allow incorporation of EMI suppression techniques. It also allows the EMC engineer to try new ideas for EMI control.

After completion of test, rework, and retest, a report will be generated by the testing agency and submitted to the procuring activity for review and approval. The test report is required by MIL-E-6051D for the systems tests and by MIL-STD-462 for the subsystems/equipment tests.

General Description of Tests

This section describes the test requirements of MIL-STD-461A and MIL-STD-462 for subsystems/equipments.

MIL-STD-461A EMI Characteristics Requirements for Equipment

MIL-STD-461A covers the requirements and test limits for measurement and determination of electromagnetic interference characteristics of electronic, electrical, and electromechanical equipments. The requirements are established to ensure that interference control is considered and incorporated into the design of equipment, and to assure the compatible operation of the equipment in a complex electromagnetic environment.

Equipments covered by this standard are divided into four groups that describe the class of equipment, and subgroups that describe the specific type of equipment. The four classes are as follows:

I Communication-Electronic (C-E) Equipment. Any item, including subassemblies and parts, serving functionally in electromagnetically generating, transmitting, conveying, acquiring, receiving, storing, processing, or utilizing information in the broadest sense. This includes transmitters and receivers using antennas.

II Non-Communication Equipment. This class includes equipment generating RF energy for use other than for information or control. It also includes electrical equipment and accessories for vehicles and engines.

III Vehicles, Engine-Driven Equipment. This class includes tactical vehicles, engine generators, special purpose vehicles, engine driven equipment, and administrative vehicles.

IV Overhead Power Lines.

For a subclass breakdown, refer to Table I of MIL-STD-461A.

At present, MIL-STD-461A does not list authorized test instrumentation needed for performance of the tests. The approved list will be in a revision of MIL-STD-461A. In the interim, EMC instrumentation that can measure the parameters of MIL-STD-461A may be used, when approved by the procuring activity for the specific equipment in question. The accuracy of measurements made in accordance with MIL-STD-461A must be: frequency accuracy ±2 percent and amplitude ±2 dB.

Not specifying measuring equipment results in the use of inadequate equipment. For example, MIL-B-6181D does not permit use of the Stoddart NM-20 field intensity meter because of its outmoded design. MIL-STD-461A implies that it can be used.

MIL-STD-462 Electromagnetic Interference Characteristics, Measurement of

MIL-STD-462 provides a detailed description of various ways to measure the electromagnetic emission and susceptibility characteristics of electrical, electronic, and electromechanical equipment. Measurement of these characteristics is necessary to determine if the equipments meet the electromagnetic compatibility requirements of MIL-STD-461. Each test method is identified by a four character descriptor such as CE03. The two letters identify the type of test as follows:

Conducted emission	CE–
Radiated emission	RE–
Conducted susceptibility	CS–
Radiated susceptibility	RS–

A complete list of the test methods contained in MIL-STD-462 appears in Table 9-1. Each equipment being tested to determine compliance with the requirements of MIL-STD-461 requires the use of only certain of the test methods. The type of equipment under test determines which test methods are

applicable. MIL-STD-461 divides electrical, electronic, and electromechanical equipment into classes and subclasses and indicates which test methods in MIL-STD-462 should be used for each subclass. Thus a contractor must determine which subclass includes an equipment before he can determine which test methods are to be used. The EMC/EMI Test Plan, required from the contractor by MIL-STD-461A, should indicate which test methods have been selected for testing each equipment. A sample of such an EMC/EMI Test Plan is in Appendix D.

Table 9-1 Test Methods in MIL-STD-462

Method	Date	Title
CE01	31 July 1967	Conducted Emission, 30 Hz to 20 kHz, Power Leads
CE02	31 July 1967	Conducted Emission, 30 Hz to 20 kHz, Control and Signal Leads
CE03	31 July 1967	Conducted Emission, 20 kHz to 50 MHz, Power Leads
CE04	31 July 1967	Conducted Emission, 20 kHz to 50 MHz, Control and Signal Leads
CE05	31 July 1967	Conducted Emission, 30 Hz to 50 MHz, Inverse Filter Method
CE06	31 July 1967	Conducted Emission 10 kHz to 12.4 GHz, Antenna Terminal
CS01	31 July 1967	Conducted Susceptibility, 30 Hz to 50 kHz, Power Lead
CS02	31 July 1967	Conducted Susceptibility, 50 kHz to 400 MHz, Power Lead
CS03	31 July 1967	Conducted Susceptibility, 30 Hz to 10 GHz, Intermodulation, Two Signal
CS04	31 July 1967	Conducted Susceptibility, 30 Hz to 10 GHz, Rejection of Undesired Signals at Input Terminals (2-Signal Generator Method)
CS05	31 July 1967	Conducted Susceptibility, 30 Hz to 10 GHz, Cross-Modulation
CS06	31 July 1967	Conducted Susceptibility, Spike, Power Leads
(T) CS07	31 July 1967	Conducted Susceptibility, Squelch Circuits
CS08	31 July 1967	Conducted Susceptibility, 30 Hz to 10 GHz, Rejection of Undesired Signals at Input Terminals (1-Signal Generator Method)
RE01	31 July 1967	Radiated Emission, 30 Hz to 30 kHz, Magnetic Field
RE02	31 July 1967	Radiated Emission, 14 kHz to 10 GHz, Electric Field
RE03	31 July 1967	Radiated Emission, Spurious and Harmonic Emissions 10 kHz to 40 GHz
(T) RE04	31 July 1967	Radiated Emission, 20 Hz to 50 kHz, Magnetic Field
RE05	31 July 1967	Radiated Emission, 150 KHz to 1 GHz, Vehicles and Engine-Driven Equipment
RE06	31 July 1967	Radiated Emission, 14 KHz to 16 Hz, Overhead Power Lines
RS01	31 July 1967	Radiated Susceptibility 30 Hz to 30 kHz, Magnetic Field
RS02	31 July 1967	Radiated Susceptibility, Magnetic Induction Fields
RS03	31 July 1967	Radiated Susceptibility, 14 kHz to 10 GHz, Electric Field
RS04	31 July 1967	Radiated Susceptibility, 14 kHz to 30 MHz

Test Conditions

Highlights of the required test conditions are described below.

The ambient electromagnetic level with the test sample de-energized must be at least 6 dB below the allowable emission or susceptibility limits. MIL-STD-462 describes a technique for performing measurements if the test site does not meet these limits.

The ground plane should consist of copper or brass at a minimum thickness of 0.25 millimeters for copper or 0.63 mm for brass and 2.25 square meters or larger in area. It shall be bonded to the shielded enclosure so that the DC bonding resistance is 2.5 milliohms or less. The bonds must be not more than 90 centimeters apart. For equipment mounted on a metal test stand, the test stand should be considered part of the ground plane and should be bonded accordingly.

The test sample must be operated in all necessary modes of operation and the controls must be set as prescribed in the instruction manual or as specified in the Test Plan.

Actual or simulated signal inputs required to activate, to use, or to operate the equipment are used.

The equipment and the interconnecting cable assemblies and supporting structures simulate actual installation and usage.

The antenna terminals of C-E equipments using antennas must be terminated with a shielded dummy load as appropriate for the equipment under test. The load shall be such that the normal emission or susceptibility of the equipment is not affected at the frequencies of concern or the voltage standing wave ratio (VSWR) of resistive dummy loads and/or attenuators.

Test Point Description

To a large degree, the number of test points and the criteria for selection determine the adequacy of a given system test. Information is required about each test point so that the procuring activity can evaluate the scope of the proposed test. The criteria for selection of test points must be included in the Test Plan. There would normally be specific reasons why particular test points were selected, or reasons for omission. Some of the factors that might influence selection are criticality of the circuit, test data specifically required by MIL-STD-461A or MIL-STD-469, analysis of system parameters, and accessibility. To aid in test point selection, the testing organization must establish some general guidelines. These guidelines or criteria are to be presented in the Test Plan.

All aircraft subsystems must have a number of critical test points defined that will represent functions to be monitored. The test points are selected by the following criteria:

1. As a requirement of MIL-F-6051D, Categories I and II equipment power input terminals
2. Equipment that had been tested at the component level and indicated potential susceptibility

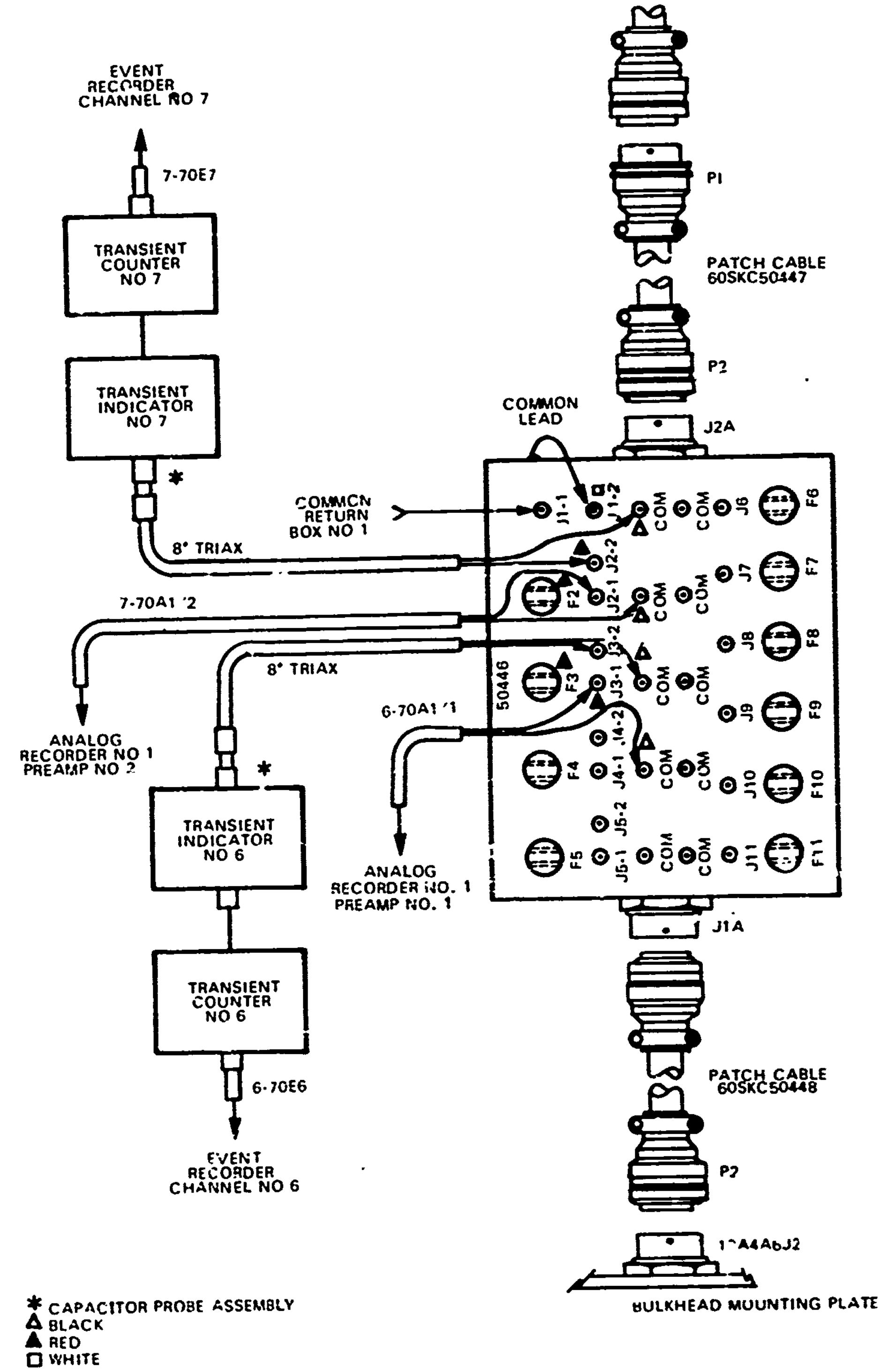


FIGURE 9-5 BREAK-OUT BOX FOR MONITORING CIRCUITS

3. Equipment and circuits deemed critical by the function performed

Whenever possible, critical test points are determined by probing during developmental testing. When this cannot be done, the point will be selected on the basis of subsystem and system analysis. Where test points do not exist, critical functions should be monitored without disrupting or changing the characteristics of the output.

Different techniques are used in monitoring the information at the test points. A common technique is to use break-out boxes, which allows monitoring without interfering with the cabling and casting doubt on the integrity of the information. Figure 9-5 depicts the method of inserting a break-out box in series with the equipment. Circuits to be monitored are brought out to test points that are accessible to the monitoring equipment. To prevent feedback from the monitoring equipment, isolation components are inserted between the test point and the circuit.

The break-out box forms part of the system during the test and must conform to the same requirements set forth for the equipment. It is essential that integrity of the system cables is not degraded; therefore, in designing the break-out box, good engineering practice must be followed. The method of monitoring the information must be included in the Test Plan, with appropriate drawings and tables.

For each test point selected, certain sepcific information should be included in the Test Plan. Two such specifics are the susceptibility level at the test point and the safety margin to be verified. The origin of the susceptibility level should be indicated, such as MIL-STD-461A or MIL-STD-469 testing and design requirements. Test points should be defined by schematic connector pin numbers and by functional name. Circuit response should be detailed for the applicable test point.

All of the above except selection criteria could be presented in a test point chart as follows:

Name	Location	Suscept. Level	Frequency Response	Origin	Safety Margins
Pitch Position Feedback	2W44J2 Pin e	50 mv	12 Hz	Design Requirements	25 mv (6 dB)

Measurement Instrumentation and Techniques

A detailed description of test equipment and associated EMC instrumentation is required to evaluate the adequacy of the equipment to meet the objectives. A description of instrumentation for each test should include the sensitivity, frequency response, deflection factors, type of permanent record, and means of setting calibration. A continuation of the test point chart above could supply this information as follows:

Name	Sensitivity	Instrument	Amplifier	Galvo Response
Pitch Position Feedback	10 mv	Oscillograph	DC/0 to 5 kHz	25 Hz

Deflection Factor	Calibration	Record
1/2 inch-200 mv	Inject 100 mv	Oscillograph paper

Other relevant information should be included such as a block diagram of the instrumentation from test point to recording device, or configuration of test equipment relative to specimen under test.

Specific techniques used to verify compatibility at the instrumented test points should also be stated. One such technique that requires special attention is the operating mode or modes of the system at the time measurements are made. As an example, the measurement described in the test point chart might go to high RF power in a normal checkout sequence. To protect the EMC instrumentation and to maintain safety margin, specific arrangements of attenuator pads and couplers may be required. This is a procedural requisite that might influence the validity of other measurements, and as such should be delineated.

The EMC Test Plan describes test methods to be used in determining the interference and susceptibility characteristics of the equipment to be examined. These tests are selected by the EMC engineer based on his judgement of which ones will best fulfill the requirements imposed on the equipment under examination.

For interference measurements to be useful, measurement instrumentation and techniques must produce usable data in absolute numbers and definite units, and the susceptibility of the equipment must be proved or disproved. The field of interference measurement requires fundamental concepts of conducted and radiated signal measurements in terms of signal levels and frequency, a knowledge of the equipment under test and its functions, a knowledge of the use of many different types of measuring instruments, and an ability to interpret the measurements.

Selection of Measurement Instrumentation

A list of the required measurement instrumentation is shown in the EMC Test Plan. In preparing the Test Plan, the test sample specifications are analyzed and requirements applicable to the test are extracted. The next step is to judge which test points will best indicate a susceptible condition. After selection of these parameters, the monitoring test equipment is selected to present reliable and usable data. Consideration is then given to auxiliary equipment necessary for operation of the test sample during the EMI test.

The next step is the selection of appropriate test methods, whether it is to be extracted from those specified in the EMI document or is a special test

method designed to measure certain parameters. Selecting appropriate test methods from the EMI standard is routine once the EMI parameters to be measured are known. There are cases where the parameters to be measured cannot be determined by any of the test methods described in the EMI standard. In these cases, the EMC engineer must develop test methods to determine these parameters.

The final step is the selection of measuring instrumentation. Older specifications listed acceptable measuring instruments for the specific test, but MIL-STD-461 does not. At the time of this writing, no list of acceptable measuring instrumentation has been approved for placement in MIL-STD-461. The standard merely states that the measuring instrumentation selected must have approval of the procuring activity. Therefore, instrumentation that did not have approval from other specifications because of being outmoded or for other reasons, can now be used.

Test Procedures and Techniques

Because of the wide variety of instrumentation and test methods required to perform the EMI tests, there is a corresponding variety of test configurations. Compliance with test parameters may require the use of one or all of the following procedures: tests performed in a shielded enclosure, with the sample placed on a ground plane, in an anechoic chamber, or on location. For these reasons, no simple prescribed test configuration can be assumed. Therefore, test procedures and test configurations must be used as guides in establishing the appropriate methods of determining the EMI characteristics.

Auxiliary units necessary for operation of the test sample might themselves be sources of interference, or be susceptible. The test techniques used must ensure the reliability of EMI measurements. Therefore the placement of these auxiliary units is an important factor. For example, during area EMI ambient measurement, the measured broadband interference may be found to exceed the specified limits. Or interference may be produced by a signal-simulating unit, making it necessary to place the unit outside the shielded enclosure and feed the signal into the enclosure via feed-through connectors. These peculiarities should be evaluated before formal testing to ensure integrity of the measured data.

Methods of performing the measurements are documented either in the Test Plan or in a test procedure. The test procedure is usually prepared for in-house use and is included as an appendix of the test report. The document contains the tests to be performed, and a detailed step-by-step procedure including initial calibration of the measuring instruments. When the test procedures are included in the Test Plan, descriptions of testing procedures and techniques are held to a minimum.

Outline for EMC Test Procedure

An outline of a typical test procedure is shown below.

<u>Abstract</u>

Briefly describe contents of document

Contents

Includes major paragraphs and appendices

Administrative Data

Include the following headings:

- Purpose of Test
- Applicable Documents - Specifications
- Standards, Drawings
- Test Sample Identification
- Manufacturer
- Security Classification
- Test to be Performed by
- Test Location
- Date of Test
- Disposition of Test Sample

Scope

Define the scope of the EMC tests to be performed, and identify the applicable EMC specification

Description of Test Sample

- Functional and Physical Description
- Connectors Associated with the Test Sample
- External Controls

EMI Tests To Be Performed

- Interference Tests
- Susceptibility Tests
- Tests Not Applicable
- Exceptions to EMI Control Specification

Anticipated Interference

Test Equipment

- Test Equipment Required
  - List all ground support equipment (GSE), EMC test equipment, hardware, special test interfaces, include part no., S/N and calibration dates
- Test Equipment Calibration
- Line Impedance Stabilization Networks (LISN) or Feed-Through Filters
- Test Equipment Bonding

Test Conditions

- Test Location
- Test Arrangement
- Test Sample Bonding
- External Loads
  - Describe electrical and/or mechanical loads to be used
- Lead Lengths and Position with respect to Ground Plane -
  1. Primary Power Leads
  2. Interconnecting Leads

3. Load Leads

Shielded Leads

Coaxial Cables

Test Sample Operation

1. Modes of Operation
2. Steady State Interference Test Mode
3. Transient Interference Test Mode
4. Susceptibility Test Mode
5. Functional Tests
6. Control Settings

Accuracy of Test Equipment -

Define recalibration conditions, etc.

Detailed Test Procedure

Operation of Interference Measuring Instruments

(State frequency range, detector function and calibration)

Selection of Test Frequencies

Ambient Interference Measurements

Test Limits

Describe design parameters and specify acceptable variations

Failure Criteria

List conditions that constitute failure due to susceptibility, i.e., where changes from operational test values beyond allowable limits or degradation of performance occurs

Specific EMI test procedures for each EMI test to be performed

Test No. 1 RF conducted interference (.15 Hz to 25 Hz)

Test No. 2 RF radiated interference (.15 Hz to 10 Hz)

(Continue list as required)

Test Report

Acknowledge that a test report will be prepared

Test Personnel

Acknowledge that personnel performing test will be identified in test report

Appendix I

Includes test arrangement diagram, electrical loads, test equipment list

Appendix II

Sample data sheets and graphs

Data Analysis and System Evaluation

Before EMI tests, preparation of a detailed test plan relating the proposed course of action and anticipated completion date of each significant phase of the tests is required. In general, the test plan must contain information sufficient for the planning of data reduction methods and the establishment of test reporting procedures. The test plan includes the details of the procedures when out-of-tolerance conditions are discovered during the test program.

Conformance To Specification and Standards

EMI Specifications and Standards are established as guidelines covering requirements, test limits, measurements, and determination of EMC interference, emission, and characteristics of equipments, subsystems, and systems.

Data analysis starts with the conception of the program and continues through each phase of the EMC Program. Once system requirements are established, basic parameters are used for the starting point of the data analysis. These parameters are EMC design guidelines for the design engineers and reflect the EMC specification limits required of the system.

System Analysis

System analysis is the initial approach to establishing EMC parameters based on the governing EMC document. System analysis is divided into four parts as shown in Figure 9-6: mission analysis, frequency analysis, time analysis, and interface analysis.

Mission Analysis

The mission envelope is studied to determine the equipment required. Mission analysis includes the total weapon system and the total electromagnetic environment in which the weapon system will operate, as known or predicted. The result of mission analysis is a determination of the subsystems and equipments that must be designed and shown to be compatible. At this stage, many combinations of equipment can be eliminated as shown in a typical mission profile in Figure 9-7. Each component must perform satisfactorily in accord with EMC specification limits, and must be compatible with the other electrical-electronic subsystem/equipment.

Frequency Analysis

The frequency spectrum is analyzed to determine potential interference. This aids in establishing the frequency allocation and signal levels required for each component of the system. An airborne weapon system requires two basic analyses:

1. External coupling between each pair of avionic equipments or systems, via their antennas; and, between each equipment or system and the external environment, via their antennas.
2. Internal coupling between the wiring of each equipment or system and the wiring of every other equipment or system within the aircraft and, while being serviced, with the wiring or cabling of the ground support facilities.

Frequency analysis is based upon specified, predicted, and measured performance characteristics of the equipment in the proposed system configurations obtained from the following sources:

Performance specification for equipment
MIL-STD-461 and MIL-STD-462 test results
Antenna isolation measurements, in and out of designed

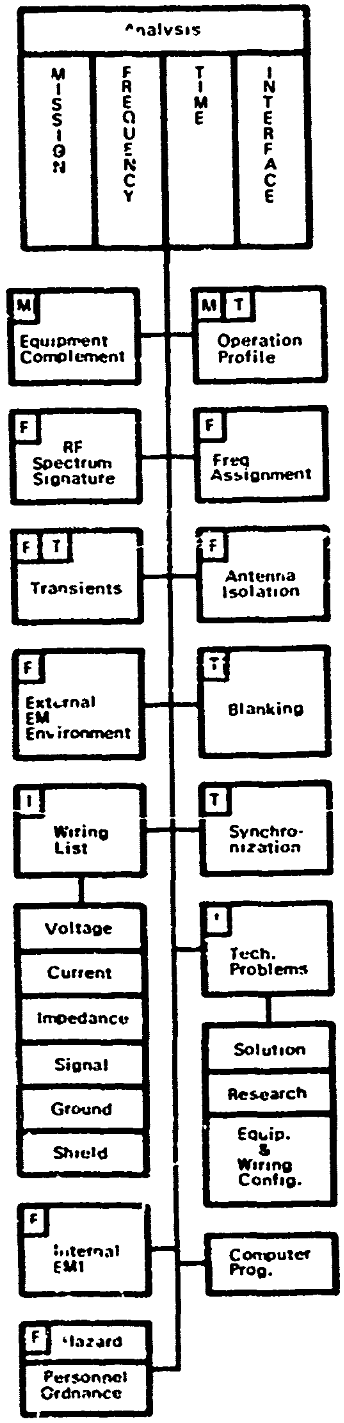


FIGURE 9-6

SYSTEM ANALYSIS PROGRAM

FUNCTION	OPERATIONAL PERIODS			
	PRE-FLIGHT	TAKE-OFF	EN ROUTE	TARGET
COMMAND	●	●	●	●
INTERPHONE	●	●	●	●
IFF	●		●	●
RADIO COMPASS		●	●	●
ALTIMETER	●		●	●
RADAR	●		●	●
DATA LINK	●		●	●
NAV LIGHT FLASHER	●	●	●	●
AUTO PILOT	●		●	●
IGNITION	●	●	●	●
FLAP MOTOR	●	●		

FIGURE 9-7

TYPICAL MISSION PROFILE

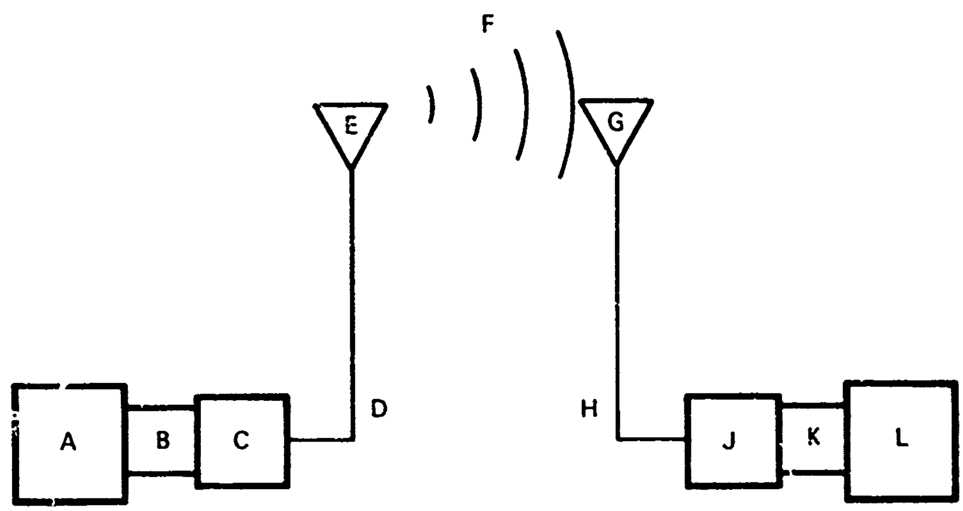
frequency spectrum, on mockups and actual airframe

Laboratory evaluation tests

EMC tests in actual environment

The analysis is amended periodically as the above information becomes more refined.

The characteristics that must be considered in a typical antenna-to-antenna coupling analysis are shown in Figure 9-8. A way to use these characteristics in determining interference that can occur between a receiver and a transmitter is shown by the following step-by-step procedure (with references to Figures 9-9 and 9-10 and to Table 9-2).



A TRANSMITTER OUTPUT SPECTRUM
B FILTER RESPONSE FUNCTION AND LOSSES
C COUPLER RESPONSE FUNCTION AND LOSSES
D CABLE LOSSES
E ANTENNA FACTOR
F SPACE LOSSES
G ANTENNA FACTOR
H CABLE LOSSES
J COUPLER RESPONSE FUNCTION AND LOSSES
K FILTER RESPONSE FUNCTION AND LOSSES
L RECEIVER SENSITIVITY

FIGURE 9-8 ELECTROMAGNETIC ENERGY TRANSMISSION AND RECEPTION

Step 1. Transmitter output spectrum - Determine and plot the spectrum at transmitter output (Figure 9-9). Enter transmitter power output for each test frequency as shown in Table 9-2, column 1.

Step 2. Receiver sensitivity - Determine and plot the receiver sensitivity, including front-end rejection characteristics (Figure 9-10). Enter receiver sensitivity for each test frequency as shown in Table 9-2, column 2.

Step 3. Transmission losses - Calculate all transmission losses due to cables, couplers, filters, antenna factors, and space (items B through K in Figure 9-8) and enter as shown in Table 9-2, column 3.

Step 4. Signal level present at receiver front-end - Subtract the total transmission losses calculated in step 3 from the transmitter power output at each test frequency determined in step 1 and enter the result as shown in Table 9-2, column 4.

Step 5. Interference situation - Compare the interfering signal level present at receiver front-end as determined in step 4 with the minimum discernible signal level of the victim receiver as determined in step 2. Those frequencies where the interfering signal level exceeds the receiver's minimum discernible signal level represent interference situations. Table 9-2, column 5 indicates interference at both frequencies (step 4 power level greater than step 2 power level in both cases).

Step 6. Reduction in range capability - The interference situation can often be converted to some specific operational parameter (such as percent reduction of range capability due to interference). The following formula shows how to determine this percent reduction in range.

$$\% \text{ Reduction} = \left(1 - \sqrt{\frac{S_{min}}{S_2}}\right) 100$$

Where:

S_{min} = Minimum discernible signal capability of the receiver (in watts) in a non-interference environment

S_2 = Signal level (in watts) required to override the interference signal in an interference environment

Calculations for the present example are entered in Table 9-2, column 6, using the step 2 power level for S_{min} and the step 4 power level for S_2. (This assumes that a desired signal could override the interference signal if the two were equal in power level at the receiver input.)

Interference must be discovered and resolved early in a system development program. Interference will be much less likely to exist if equipments in the system are designed to meet the EMC requirements of Military Standards 461, 462, and 469.

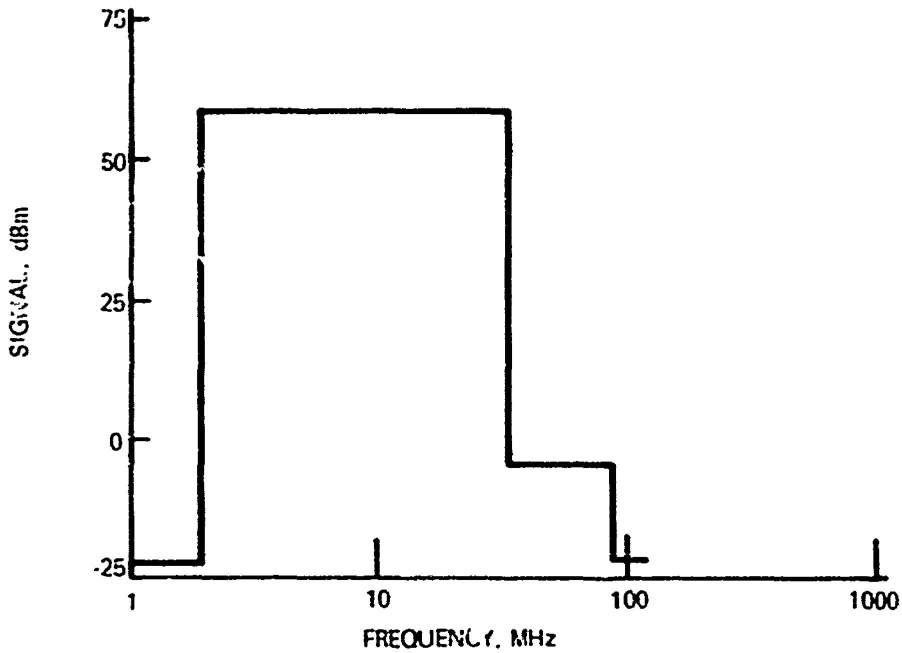


FIGURE 9-9 TRANSMITTER OUTPUT SPECTRUM MODEL

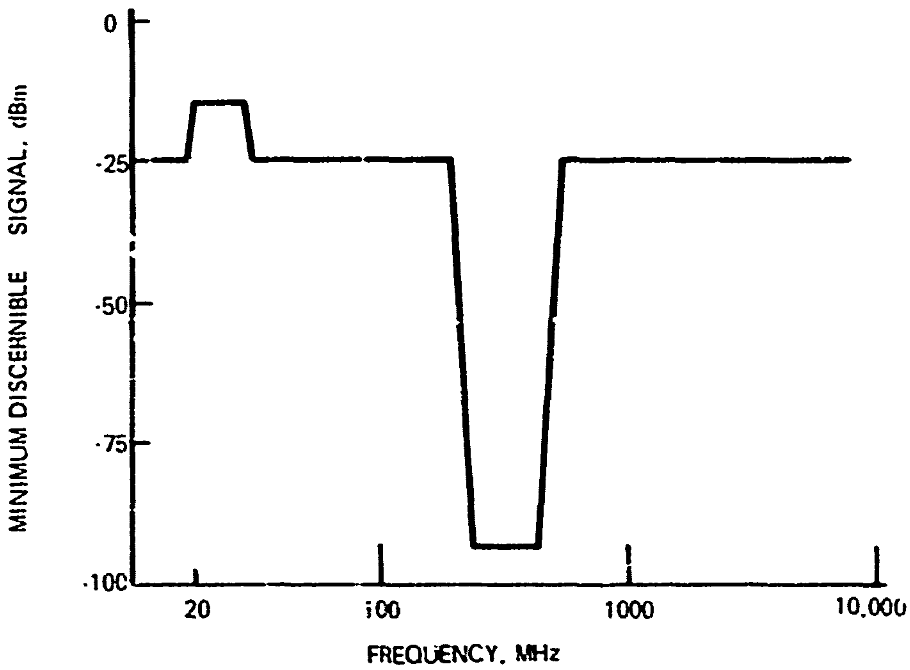


FIGURE 9-10 RECEIVER SENSITIVITY MODEL

Table 9-2
Typical Computation of Effects of Transmitter Interference on a Receiver

	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Freq MHz	dBm	dBm	dB	(1-3) dBm	(4-2) dB	Range Red. %
30	56	-25	54	2	27	95.5
300	-24	-95	54	-78	17	86.0

Time Sharing Analysis

Incompatibility problems not resolved in the frequency domain may be solved in the time domain. For example, an ECM jammer can be synchronized with a companion radar so that they operate on alternate pulse intervals. The radar receiver is thereby blanked during the jammer period, then the jammer is blanked while the radar updates its target information. Incompatibilities not resolved by either method require a change in the weapon system design.

Interface Analysis

Interfaces within the airframe system and interfaces with ground support are analyzed to determine technical difficulties associated with the particular system, and to establish the requirements for producing compatible weapon systems. The following areas are established:

1. Required state-of-the-art work
2. Equipment configuration, wiring, and grounding
3. Solutions that must be developed
4. Subsystem procurements

Computerized System Analysis

Today's aircraft has become a complex system, making system analysis a complex task. Calculating the necessary EMC parameters by hand has become obsolete now that computer programs are coming into extensive use.

By using a computer, susceptibility parameters of each subsystem and equipment can be matched with all possible interference characteristics of all system elements. The combined effect of transmitter fundamentals, spurious signals, and harmonic frequencies form a vast matrix that would take many hours of hand calculations to reconcile with all possible receptors. A computer can handle this task in a very short time.

Out-of-Tolerance Conditions

Compliance with MIL-E-6051D is achieved when the system demonstrates compatible operation without unacceptable response or malfunction. MIL-E-6051D does allow minor undesired responses that fall within the tolerance limits established by the Test Plan and that do not prevent the system from complying with its requirements.

At the subsystem/equipment level, emission and susceptibility characteristics are defined by performing specific tests as required by the governing EMC document. After these tests are over, the EMC characteristics are known and documented and the tolerance limits are established. Whether or not the subsystem/equipment met the requirements of component level qualification test has no bearing on the establishment of system tolerances.

It is assumed that any out-of-tolerance condition discovered during the subsystem/equipment level testing was either fixed and retested and/or if the out-of-tolerance conditions were considered minor, a waiver was granted by the procuring activity.

The aircraft prime contractor EMC personnel have the responsibility of defining test limits similar to those specified in MIL-STD-461. As these limits are discrete rather than continuous, the limits are usually defined as a specific tolerance. For example, a receiver is tuned for a fundamental of 300 MHz with a 6 dB bandwidth of 20 MHz, a sensitivity of -90 dBm and an image rejection at 60 dB. The receiver EMC characteristics were defined by the component level test and was qualified for integration into the system. Therefore, an out-of-tolerance condition would be indicated if an interfering signal measured during the system compatibility test fell within the receiver's characteristics as defined above.

Evaluation Of Aircraft As A Composite Weapon System

The aircraft as a composite weapon system is subjected to a comprehensive EMC test program. This test program is the culmination of the total EMC Program from the concept stage through the final configuration. The test will not only indicate the compatibility or incompatibility of the weapon system, but it will indicate how well the EMC Program was performed. It also indicates how well the prime contractor carried out its EMC contractual agreement. In essence, it marks the ability of the prime contractor to manage a good EMC Program.

Tests and evaluations are performed according to the guidelines established in the EMC Test Plan and in accord with the requirements of MIL-E-6051D. It is intended to serve as a final check on the EMI characteristics of a complete, operationally configured weapon system. The tests are designed to investigate every potential incompatibility of the system in its operational environment. For this reason, each EMC test is unique in that system test criteria and test procedures are modified to the particular requirements of the specific system. As complexity and sophistication increase, test requirements and procedures increase accordingly.

Consideration is given to the intended mission profile, the available EM environment data, and the degree to which the external environment can reduce the desired system operation.

The EMC system test and evaluation program begins in the design phase and is finalized by EMC engineers performing the EMC test. A weapon system EMC Test and Evaluation Program is outlined below:

1. *Objective*

   Evaluate EMC in accord with mission profile requirement

   Evaluate and correct existing interaction

2. *Approach*

   Preparation of Test Plan

      Translate mission requirements into test matrix

      Select test frequencies of the transmitter and receiver

      Establish hangar, ground apron, and flight plan

   Establish Procedural Detail

      Define equipment performance check

      Establish equipment operation condition

      Define equipment monitoring techniques

      Delineate test equipment requirements

   Perform EMC Evaluation Test in accord with MIl-E-6051D

   Evaluate existing interactions

Determine significance of interaction, dispose of interactions, define fixes or prepare deviation requests as appropriate.

Mission requirements are translated into a test matrix that is used as a basis of most tests. The matrix is developed from a complete list of equipment, both electrical and electronic. The list is expanded to include all modes of operation, which are typically divided into transient and steady state. The matrix is then condensed by application of the results of the component level tests, knowledge of the surrounding EM environment, and engineering experience. This reduction process continues until it creates a situation in which it would be practical to perform the necessary tests. All combinations of frequencies at which interference might occur would result in an enormous number of tests. Therefore a plan is chosen that selects the frequencies most likely to produce interaction plus some randomly selected frequencies. The selection process includes combinations covering transmitter harmonics, spurious outputs based on the EMI characteristics determined by component tests, and receiver response based on its EMC characteristics determined by the component level tests. If the test results show no interaction on the selected frequencies, compatibility is probable.

The next item under consideration is the establishment of limitations imposed by hangar, apron, and flight tests. Factors that must be considered are radiation hazards, interaction with the real-world electromagnetic environment, physical limitations, and practical limitations. For example, a certain radar cannot be operated in the shielded hangar because of radiation hazard; the trailing wire antenna cannot be extended in the shielded hangar because of physical limitations.

Sample of EMC Test Plan

Basic requirements for EMC Test Plans are set forth in MIL-E-6051D and MIL-STD-461A. The applicable specifications must be general to allow flexibility in meeting the requirements of a variety of systems and equipments. As an aid to the EMC engineer, sample test plans are provided in the appendices of this manual. Appendix C is a sample of the test plan required for an EMC system test to comply with MIL-E-6051D. Appendix D is a sample of an equipment type test plan required for an EMC test to demonstrate compliance with MIL-STD-461A.

EMC TEST REPORTS

The purpose of this subsection is to standardize the preparation and submission of the system EMC test report and to ensure that adequate information is presented for efficient evaluation of the test procedures and results

The contractor will be required to submit a complete, certified EMC test report to the procuring agency covering the results of the system electromagnetic compatibility testing. The EMC test report will be prepared by the organization performing the EMC tests. When required, the test report will be identified by a universal document number furnished by the procuring activity.

Content and Format

MIL-STD-461A and MIL-E-6051D both require that a test report be prepared in accord with MIL-STD-831. The test report is then submitted to the procuring activity for evaluation.

MIL-STD-831 delineates the format and content criteria to be used in the preparation of test reports covering systems, subsystems, equipment, components, and parts. The purpose of the standard is to foster uniformity in the portrayal of test results. It also provides for greater ease in evaluation of design suitability and performance capabilities of the unit under examination.

The EMC test report contains the conclusions of the testing agency and/or qualified persons who witnessed the test, complete records of the test including data sheets, test points, test point selection criteria, test frequencies, irregular functions of the specimen, chronological test logs, test procedures, ambient electromagnetic environment in the check-out area, and a complete description of all test equipment. Schematics and data on filters and other suppression devices should also be included.

General requirements and detail requirements of format and content criteria of the EMC test report are specified in MIL-STD-831. MIL-STD-461A paragraph 4.4 provides for modification to accommodate matters peculiar to the EMC test report and specifically requires the inclusion of certain detailed test information to verify validity and repeatability of the tests.

Use of Appendices

A separate appendix must be used for each test. Each appendix includes the applicable test procedure, data sheets, graphs, illustrations, and photographs. Each appendix is identified on each page and in the table of contents.

The log sheets are included in a separate final appendix. Definitions of specialized terms or word usage are in another appendix. The test report should avoid the use of abbreviations.

All parts of the report should be concisely and clearly written. Graphical and tabular presentations are to be self-sufficient in that enough test methods and test specimen information should be contained to provide complete graph or table identification.

Separate data sheets are to be used for each individual test and for data taken with different measurement equipment. If different antenna locations are used during radiation tests, each different antenna location should be considered as a separate test. Each lead on which conducted EMI tests were performed should be considered as a separate test. Each data sheet must include such information as test date, personnel performing the test, type of test, special test conditions, abbreviated test configuration, and test specimen identification including serial numbers. The data recorded should provide the following information as applicable: frequency, ambient interference level, meter indications, cable losses, antenna factor, specification limit, bandwidth factor, and detector function used.

The test report is submitted to the procuring activity to fulfill the contractual agreement and to serve as an input to system analysis. EMI characteristics of the test sample as documented in the test report will be used as a base for establishing system EMC limits.

GENERAL ACCEPTANCE TEST

In addition to the detailed electromagnetic compatibility tests performed upon samples of the contract end product, MIL-E-6051D paragraph 4.3.2 requires that each production unit be subjected to a limited General Acceptance Test to confirm continued compliance with EMC requirements.

The General Acceptance Test is a limited quality assurance test applied to each production system other than those upon which a complete EMC compliance test is performed.

Procedures for the General Acceptance Test should be specified as part of the EMC Test Plan. All test results, including any objectionable interference or degradation of performance, must be properly recorded.

SERVICE APPROVAL AND BOARD OF INSPECTION AND SURVEY TRIALS

Board of Inspection and Survey (BIS) trails fo: ircraft require the contractor to demonstrate in accord with MIL-D-8708B, the performance and compatibility of the complete aircraft. MIL-D-8707B, Paragraph 3.25.2.10,

specifies that the contractor shall report on electromagnetic compatibility and interference characteristics as part of the Avionics System Demonstration Data Report This report is submitted to the Board of Inspection and Survey via the Commander, Naval Air Test Center, at least 60 days before the release of the aircraft for INSURV electronic and armament trials.

BIS trials are performed on production samples of the aircraft that are completely configured with armament system, electrical and electronic equipments, and are in normal operating condition. System operational tests will be performed before EMC testing to assure continuance of normal performance.

The purpose of the BIS trial is to verify that the aircraft can perform its mission. Because the BIS trial is an overall test, there is a danger that the EMC aspects will be slighted unless an obvious major interference-related malfunction appears.

At present there are no detailed military specifications for BIS trials on avionic systems, nor is there likely to be any, because of the wide variance in aircraft configurations. BIS trial testing should conform to the general requirements of MIL-E 6051D and MIL-D-8708B. Detailed BIS trial procedures for EMC can be developed from the manufacturer's test procedures, especially the EMC Test Plan, which has had the advantage of repeated reviews by the Electromagnetic Compatibility Advisory Board and by the contractor's EMC engineering group.

It is the policy of INSURV to accept EMC test data from any source which, in the judgement of the activity conducting the trials, is deemed to be valid and fully representative of the production article undergoing trials. Properly validated demonstration data are of assistance to INSURV and thus decrease the time required for trials.

IN-SERVICE SUPPORT

Once the system is turned over to a service command for operational use, the EMC attributes designed into it must not be allowed to degenerate. Avionics equipments and assemblies must be opened from time to time for inspection and maintenance or to replace defective parts. Shock, vibration, and corrosion can affect shields, bonds, and connectors. Fasteners and gaskets are not always given proper attention. Unless maintenance and operating personnel are aware of the EMC properties of all the items that go into making the system electromagnetically compatible and are aware of the reasons for their use, the effectiveness of EMC will deteriorate through negligence and inattention to detail. Operational commands may have to initiate educational programs to instill EMC awareness and maintenance practices into maintenance and support personnel.

In addition to the training and maintenance program for the system itself, the command to which the system is assigned should develop a program for reducing electromagnetic interference in the environment in which the system operates. An aircraft radar recently out of overhaul can have its mixer crystals damaged by nearby radar before the first post-overhaul flight of the aircraft.

Every tube or transistor in a receiver can be ruined by voltage or current spikes generated by the starting cart. A poorly-arranged UHF frequency assignment plan can place one busy channel on the image frequency of another.

To help in the educational program by providing information on equipment characteristics and on standards and specifications, various sources of electromagnetic compatibility information are established in military, government, and civilian agencies. These agencies are repositories for EMC data storage and retrieval, and provide information and guidance on standards, specifications, design characteristics of components and equipments, and other matters related to EMC. Access to such information is on a need-to-know basis.

Navy Sources of EMC Support

Navy contact points for EMC information are:

1. Navy aircraft (bonding, EMC, lightning, etc.):
   Navy Air Systems Command
   Attn: AIR-53356
   Washington, D. C. 20390

2. Navy aircraft development, test, and evaluation:
   U. S. Naval Air Test Center
   Patuxent River, Maryland

NATC PAX operates as lead laboratory for the Naval Air Systems Command on Navy-wide development, test, and evaluation programs of aircraft and aircraft systems. NATC PAX also supports the Navy Material Command Board of Inspection and Survey in the conduct of aircraft weapon system acceptance trials.

3. Shore and base facilities:
   Navy Facilities Engineering Command
   Code 041E1
   Washington, D. C. 20390

4. Ships:
   Navy Ship Engineering Center
   Code 6179C05 & 06
   Washington, D. C. 20390

5. RDT&E:
   Western Area Frequency Coordinator
   Point Mugu, Ca. 93042

Army Sources of EMC Support

1. Army avionics:
   Army Avionics Laboratory
   USA Electronics Command
   ACCF-SELAC-T/EMC
   Bldg. 2532
   Fort Monmouth, N. J. 07703

The Army Avionics Laboratory at Fort Monmouth has the responsibility for research and development of instrumentation and methodology for EMC investigations.

2. Aircraft systems and international standardization:
   USA Avionics Systems Command
   Attn: AMSAV-R-MN
   P. O. Box 209, Main Office
   St. Louis, Mo. 63166

3. Civil engineering:
   USA Corps of Engineering
   Ohio River Division Laboratories
   Instrumentation and Special Studies Branch
   5851 Mariemont Avenue
   Cincinnati, Ohio 45227

4. US Army Electronics Command
   Attn: AMSEL-CG-EC
   Ft. Monmouth, New Jersey 07703

5. Electroexplosive devices and ordnance:
   Commanding Officer
   Frankford Arsenal
   Attn: SMUSA-N-1110
   Philadelphia, Pa. 19137

   Picatinny Arsenal
   Attn: SMUPA-PT-1
   Dover, N.J. 07801

6. Automotive equipment:
   Army Tank/Automotive Command
   10 Mile Road and Van Dyke
   Warren, Mich. 48089

7. Missiles and space:
   Redstone Arsenal
   Attn: AMCPM-MBES
   Huntsville, Ala. 35809

Air Force Sources of EMC Support

1. Air Force Avionics Laboratory (VWE-1)
   Wright-Patterson AFB Ohio 45433

The Air Force Avionics Laboratory is responsible for EMC research and development for aerospace systems and equipments. Programs have been established for interference reduction, static electricity, lightning, micro-electronics.

2. Aeronautical Systems Division (ASNAC-30)
Wright-Patterson AFB Ohio 45433

The Aeronautical Systems Division has the primary EMC engineering responsibility for support of aerospace oriented systems.

3. Rome Air Development Center (EMNCI)
Griffiss AFB, N.Y. 13440

The Rome Air Development Center is responsible for EMC research and development for systems and equipments intended for ground oriented missions.

4. Hq Ground Electronics Engineering Installation Agencies (GEESM)
Griffiss AFB, N.Y. 13440

The Ground Electronics Engineering Installation Agencies have the primary EMC engineering responsibility for support of ground oriented systems and equipments.

5. Hq Electronics System Division (ESLE)
L. G. Hanscom Field
Bedford, Mass. 01730

The Electronics System Division has the responsibility for acquisition of ground oriented systems and equipments.

6. 280 2nd Inertial Guidance and Calibration Group
(HCLTE)
Newark Air Force Station
Newark. Ohio 43055

This group is attached to AFLC, and is the Air Force bureau of standards.

EMC Support from Other Government Organizations

EMC contact points for National Aeronautics and Space Administration (NASA) are:

1. National Aeronautics and Space Administration
Code MAR, Apollo Program Office
Washington, D.C. 20546

2. Marshall Space Flight Center
R-QUAL-PIE
Huntsville, Ala. 35809

3. Goddard Space Flight Center
Code 324-1
Greenbelt, Md. 20771

4. Lewis Space Flight Center
MS 500-109
21000 Brookpark Road
Cleveland, Ohio 44135

EMC contact point for the Federal Aviation Agency is:

1. Radio Technical Committee for Aeronautics
   2000 K Street, NW
   Washington, D.C. 20006

EMC contact point for the Electromagnetic Compatibility Analysis Center (ECAC) is:

1. Electromagnetic Compatibility Analysis Center
   North Severn
   Annapolis, Md 21401

Civilian Agencies and Societies

Several civilian agencies concerned with EMC can provide information and standards:

1. SAE Committee AE-4
   Society of Automotive Engineers Inc.
   Two Pennsylvania Plaza
   New York, N.Y. 10001

The SAE has an extensive technical effort in support of aerospace systems and equipments. Committee AE-4, which deals with electromagnetic compatibility, has various projects to develop EMC reports for industry. The committee is organized so that the participants do not represent their own organizations, thus enabling the best technical recommendations to be developed.

2. Committee G-46
   Electronics Industries Association
   2001 Eye Street, NW
   Washington, D.C. 20006

Committee G-46 of the Electronics Industries Association also has a number of EMC projects. This committee is organized with participants representing their own organizations in order to obtain an industry viewpoint. Some of the G-46 projects are: designers guide, EMI films, evaluation measurement techniques, system effectiveness, system power quality, FCC EMI controls, and EMI requirements for commercial equipment.

3. Institute of Electrical and Electronics Engineers
   345 East 47th Street
   New York, N.Y. 10017

The IEEE Group on EMC has sponsored an annual EMC symposium and also periodically publishes various EMC proceedings and transactions. Their prime interest is in the origin, characteristics, and control of interference, although their publications touch on other EMC aspects.

4. National Fire Protective Association
   60 Batterymarch Street
   Boston, Mass., 02110

The NFPA is usually not considered an EMC-oriented organization but NFPA has developed a number of standards that directly involve EMC. It is strongly recommended that aircraft systems EMC engineers become familiar with the NFPA and its documents. A number of NFPA documents have been accepted as United States of America Standards. Among the more important NFPA publications which affect EMC are:

NFPA STD	*SHORT TITLE*	*USA STD*
70-1962	*National Electrical Code*	*C1-1962*
77	*Static Electricity*	
78-1963	*Lightning protection*	*C5.1-1963*
325M	*Flammable Liquids, Gases, Solids, Fire Hazard Properties*	
407-1965	*Aircraft Fuel Service*	*Z119.1-1966*
409	*Aircraft Hangars*	
495	*Explosives and Blasting Agents*	

CONCLUSION

The effect of EMC implementation and control on the design of a system may be summarized by examining the applicability of EMC to the six stages of the systems cycle. The stages of the systems life cycle are described in Chapter 3, although not all programs follow the same path. The EMC requirements span the entire program activity, from concept formulation through each stage to the end of its in-service support period. Furthermore, the life cycle can be considered a closed loop, since experience and information gained at each stage feeds back into the cycle in the form of improvements in specifications and standards, equipment and component design, EMC organizational control and training, and test and evaluation procedures. Information from previous development cycles becomes the foundation of follow-on programs through the efforts of ECAC and the several military EMC support groups.

In very broad terms, the EMC organizations of the military and industry are responsible for assuring that the final product is electromagnetically compatible in all its various parts by putting into effect the necessary managerial and technical controls required during each phase of the program. The controls to meet this responsibility are procedures, specifications, and guidelines. The controls are a function both of the complexity of the program and of the program phase to which the control is applied.

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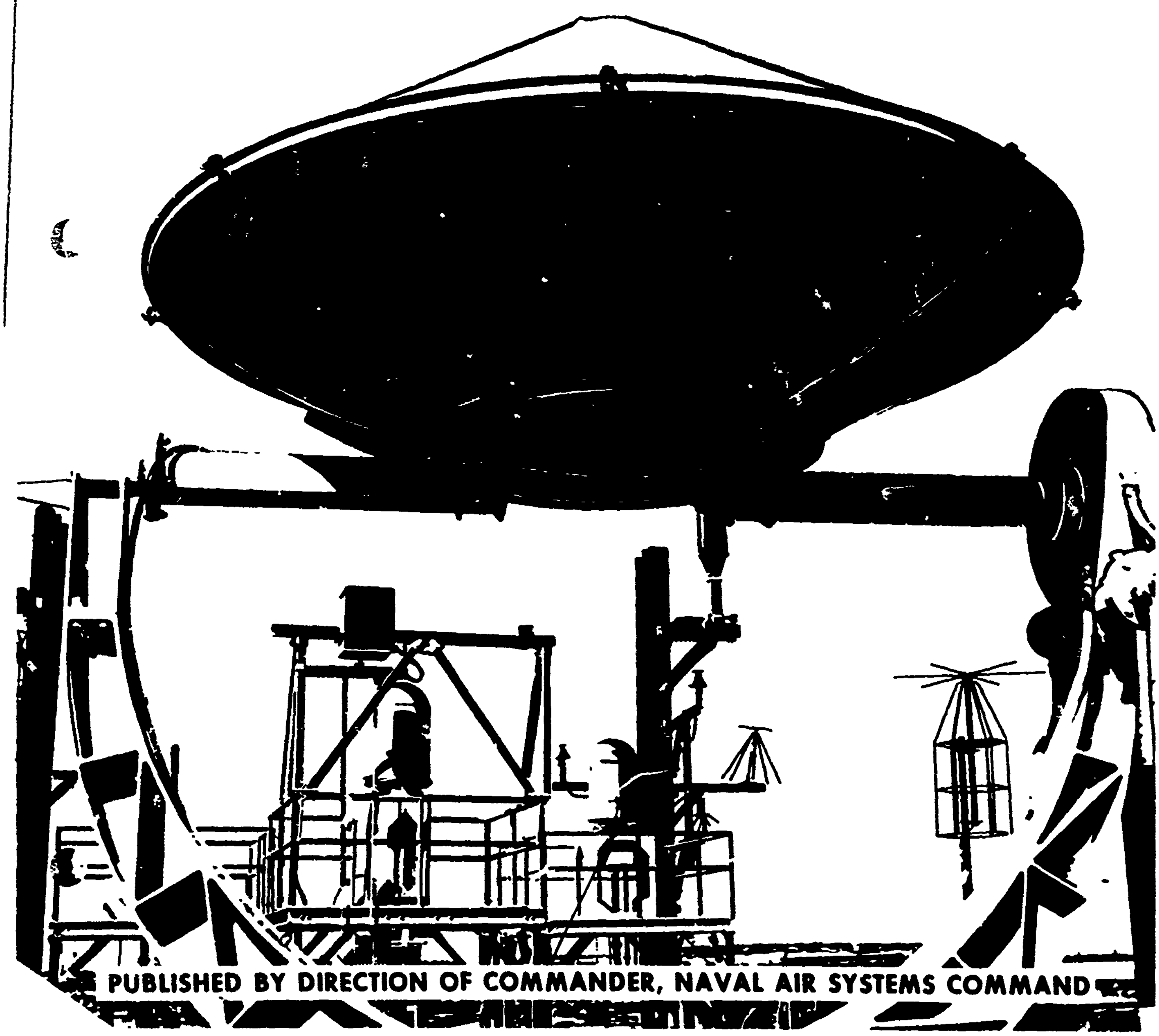
NAVAIR 5335

NAVAL AIR SYSTEMS COMMAND

ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 10



PUBLISHED BY DIRECTION OF COMMANDER, NAVAL AIR SYSTEMS COMMAND

NAVAIR EMC MANUAL

CHAPTER 10

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INTRODUCTION

The complexity and interdependence of modern electronic systems have made imperative the use of the engineering and application of formal techniques and procedures called systems engineering or systems analysis. The use of formal procedures helps to prevent overlooking important elements of the system design, which must include reliability, feasibility, compatibility, and cost-effectiveness, in addition to the practical equipment and systems specifications required to integrate the final system.

Systems engineering touches on all the engineering disciplines. Application of systems engineering in a physically small, highly complex communications and electronics environment, such as that in a naval aircraft, must consider a variety of electrical and electromagnetic phenomena and communications aspects, including analog and digital signals, spectrum use, bandwidth, noise, and distortion. The systems engineering approach includes not only technological factors; administrative factors involving cost effectiveness, planning, scheduling, and contracts must also be considered.

The systems engineering approach requires that the problem be divided in several ways, conceptually, organizationally, and technically. One grouping of systems engineering elements proposed by Machol* includes:

1. Chronological phases
2. Logical steps of the system design
3. Mathematical and scientific tools of the system design
4. Functional parts of the system
5. Administratively designated subsystems

Machol indicates that elements of these subdivisions, while coexistent, are not equivalent or spread along a continuum. They are orthogonal vectors in system space, and this multidimensionality must be borne in mind if the system design process is to be understood.

A fundamental objective of systems design in naval aircraft systems is to maximize the performance of the weapon system and to minimize risks associated with EMI. Obviously, there are indications where improving one of these factors will cause a commensurate reduction in the effectiveness or safety of one of the others. Thus, we have trade-off analyses in which, for example, we compare the cost and weight of supplying extra EMC performance or reduced probability of interference within the aircraft system with that of aircraft range and maneuverability, as well as cost. In cost effectiveness studies, we attempt to maximize the effectiveness of this system for its given fixed cost, or to minimize the cost for a given fixed effectiveness. Because it is generally impossible to find a single number that realistically represents the effectiveness of a complex system, there is a considerable amount of art as well as science in systems engineering. The use of systems engineering techniques in assuring EMC in naval air systems includes the following prime engineering aspects:

*Machol, R. E. (ed), et. al., System Engineering Handbook, New York,: McGraw-Hill Book Co., 1965, pp. 1-3 to 1-13

1. Analysis if the system enviroment, including feasible interfering sources, interference victims, coupling paths, and propagation elements, including both functional and non-functional electrical and electromagnetic elements.
2. Prediction and analysis to assess the probabilities of the occurrence and severity of interference throughout the weapon systems mission
3. Use of the proper design techniques for EMC as a way to avoid EMI problems.
4. Testing and validation as tools for improving and refining EMC prediction
5. Application of appropriate and cost-effective EMC suppression, correction, and retrofit measures.
6. Requisite planning and management required throughout the weapon system cycle

The goal of the EMC systems engineering approach is to control EMI by considering interference scurces, propagation losses, and receptor equipment susceptibility. If interference is predicted, design techniques applied at the most advantageous portion of the system can be used to reduce emission or susceptibility to acceptable limits.

Attempts to decrease interference by controlling unnecessary emissions have met with some opposition on the basis of both economy and performance. However, the electromagnetic compatibility problem is growing with the increasing number of operational and experimental radars and communication systems operating in a limited portion of the spectrum. When these factors are added to the demand for increased transmitter power and improved receiver sensitivity, the problem becomes more complex.

The increasing pressure to accommodate more stations and services, in the face of advancing equipment technology, has required the development of specifications and regulations for spectrum conservation. These regulations establish more stringent limits on unnecessary emissions and the controlled use of necessary emissions. An example of such a specification is MIL-STD-469, which governs the spectrum control of new radar systems. This document specifies limits for spectral density of radiated-power at frequencies outside the primary emission band. Trade-off decisions are usually made on the basis of the least life-cycle cost, chosen from a number of acceptable alternatives. For each alternative suggested, an EMI prediction must be made. When EMI is found or predicted, possible ways of minimizing its impact upon life-cycle cost must be investigated, and acceptable means presented for consideration in the decision-making process.

EMI analysis, prediction, and trade-off techniques must be started as soon as a concept is formulated; continued through the development and design stages; and finally, verified in the operational phase.

This chapter deals with the most important engineering aspects of systems engineering used in promoting and obtaining electromagnetic compatibility in naval aircraft weapon systems.

INTERFERENCE GENERATING SOURCES

GENERAL

Interference in NAVAIR systems can be generated in principle by any electronic or electromechanical device aboard the aircraft. In practice, however, the sources of interference are primarily those electronic and electromechanical devices that involve relatively high power, current, or voltage levels. These would typically include radar systems, countermeasures equipment, motors, servo systems, and certain types of lighting.

Communications transmitters, radar systems, and countermeasures equipment are all intentional generators of high level radiated electromagnetic energy. Other sources, such as control systems and radio receiving equipment are intentional generators of RF signals, which are not radiated but are necessary for equipment operation. An example of this type of signal is a receiver local oscillator. RF signals that are either transmitted or generated intentionally belong to a class known as functional signals.

The chief attribute of functional signals from a systems engineering viewpoint is that since they are intentionally generated, their frequency is predictable.

The emissions from these sources are generally relatively coherent in nature, with the exception of pulse radar, countermeasures, transmitters, and certain broadband communications sytems.

The emissions from intentional transmitters are usually the highest level of interfering signal present in the aircraft. For this reason, the interference from this source is usually greater than that from other sources.

Unintentional emitters of electromagnetic energy, such as motors, servo systems, digital processors, teletypewriters, and certain types of lighting, produce emissions that are generally broadband. Since the radio frequency emissions from these devices are not necessary to the function the device is performing, the resultant interference is said to be incidental. The chief aspect of incidental interference, from a system design viewpoint, is that it is not readily predictable.

Incidental interference is not, as a general rule, as intense as that resulting from functional sources. It would be natural, therefore, to assume that relatively little incompatibility results from individual sources. This, however, is not the case. The seriousness of incidental interference stems from its lack of predictability. The EMC system design is primarily developed on predictions of the influence of functional sources. Incidental interference is often not discovered until the system is configured.

In this chapter, the main concern is with systems engineering. Therefore, the major concern is with characteristics of emissions from sources on board the aircraft, since these sources are those to which EMC design methods can be applied.

FUNCTIONAL SOURCES

Functional sources consist basically of intentional communications and non communications transmitters, and those non intentional emitters that use radio frequency signals internally.

Communications transmitters consist of those devices used in voice and data air-to-air and air-to-ground circuits. Communications transmitters use a wide variety of modulation schemes, including AM, FM, single sideband, and FSK. Each type has a unique spectrum characteristic and poses different EMC hazards.

Other equipment, such as receivers, use radio frequency sources necessary for functional applications within the equipment.

The initial setup in reducing the EMC hazard posed by functional sources, is to identify the frequency spectrum characteristic of the emitted signal. In the case of a transmitter, compatibility can often be achieved merely by assigning the transmission frequency to some portion of the spectrum where little interference to receiving equipment occurs. In the case of interference from unintentional emission of functional signals, solution of the problem either lies in shielding the equipment or in designing it so that the functional signal does not occupy critical frequency spaces.

Communications Transmitters

Communications transmitters produce, in addition to the intended transmission, emissions associated with a variety of functional signals. Most of the latter accompany various frequency conversion processes necessary to develop an output on the desired frequency. In general, the conversion becomes more complicated as the operating frequency of the transmitter is increased, since a prerequisite to frequency stability is to start with a relatively low frequency oscillator.

Other emissions, in addition to the intended signal, include harmonics, excessive modulation or splatter, final amplifier noise, and spurious responses, including parasitics. Some of these effects can be reduced or eliminated with good design practices, while other effects are difficult to eliminate and, therefore, are more or less inherent in transmitter operation. As an example of these effects, the design of a typical single sideband voice transmitter operating in the high frequency range will be considered. A block diagram of the hypothetical transmitter is given in Figure 10-1. As do all transmitters, the single sideband voice equipment accepts a baseband signal and converts it to a high-level, modulated RF signal. This function is initiated using a low level balanced modulator scheme. The balanced modulator generally operates at a low frequency, typically 455 kHz. The modulated result consists of the two AM sidebands (upper and lower) and a negligible 455 kHz carrier level. The total bandwidth of the signal is equal to twice the highest audio frequency present in the base baseband signals.

At this point, two functional signals have been generated:

1. The 455 kHz local oscillator signal
2. The (double sideband) DSB modulated result

If the transmitter is not properly shielded, these functional signals can be emitted with enough intensity to interfere with reception of signals on this frequency.

The DSB modulated signal is then applied to a filter that attenuates one of the two sidebands, producing a single sideband signal. Note that, as of this point, all of the functional signals that have been generated occur at the same frequency, regardless of the selected transmission frequency.

To convert the 455 kHz SSB signal to the desired output frequency, it is necessary to use a mixer scheme. In the simple hypothetical HF transmitter, only a single mixer is used. In complex VHF and UHF transmitters, frequency conversion may be done in several stages

The operating frequency of the transmitter is established by the frequency of the local oscillator used in the mixer. In the example, the oscillator could operate either 455 kHz above or below the desired output frequency. Assume, for instance, that the oscillator frequency is below the operating frequency of the transmitter, and an output frequency of 4.455 MHz is desired. The oscillator will, therefore, operate at 4.000 MHz. It is a discrete CW signal, and is a potential source of EMI.

In addition to the desired sum product of 4.455 MHz, a difference product at 3.545 MHz is produced, which is an SSB modulated signal. If good design practices are used, the frequency response of the following stages will be adjusted so that negligible energy at these frequencies is produced at the output. If, however, the driver amplifier or power amplifier is mistuned, a significant amount of power could be radiated on these frequencies.

In a single sideband transmitter, the driver and final power amplifier are both operated as linear amplifiers. If either, however, exhibits nonlinearity, various frequency products may be created, usually resulting in a form of splatter such as modulation related emissions near the operating frequency. Nonlinearities can also result in output at harmonic-related frequencies.

In addition to emissions produced by nonlinearities, all final amplifier stages produce a broadband noise emission. The noise is random and has its origin in thermal noise processes occurring at the next to last amplifier input. The bandwidth of the noise is determined by the frequency response of the tuned circuit used in the final amplifier.

In most transmitters, the output tuned circuit is considerably broader in response than the modulation bandwidth of the signal. Final amplifier noise, therefore, can become a serious source of interference to receivers operating near the transmitter frequency.

The example given above listed some of the principal EMC hazards associated with a typical HF SSB voice transmitter. In this type of transmitter:

1. Modulation takes place at a low level
2. Frequency conversion is accomplished solely by mixers
3. The final amplifier is linear

As such, the SSB transmitter represents only some of the possible EMC hazards developed by transmitters in general. Many transmitters use high level modulation, accomplish frequency conversion by multiplication in one or more stages, and use nonlinear final amplifier designs. An example of an AM transmitter employing all of the above is illustrated in Figure 10-2

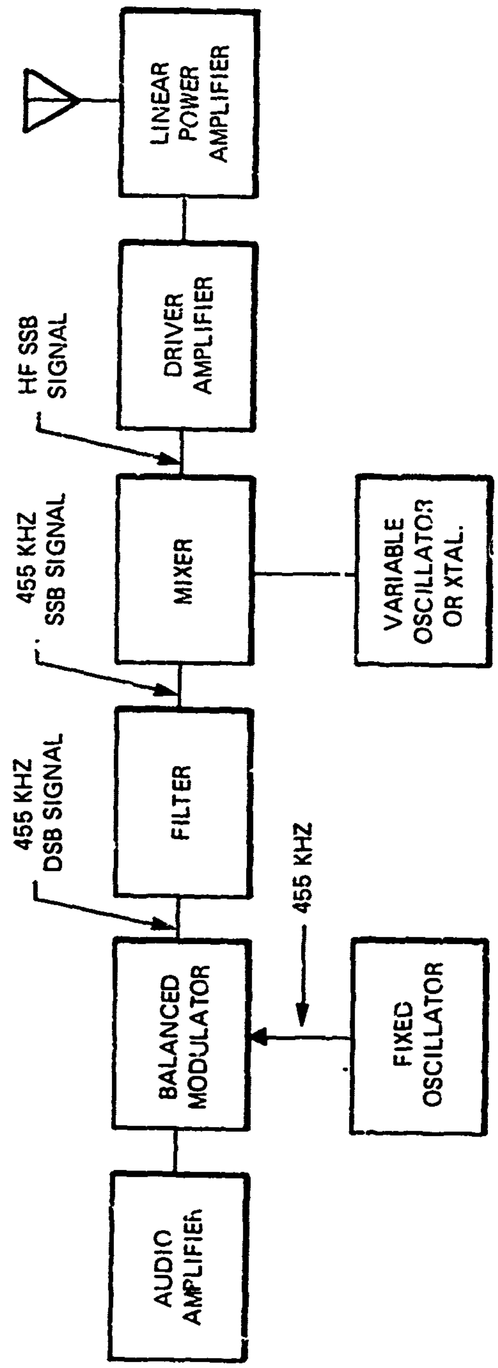


FIGURE 10-1 HYPOTHETICAL HF SINGLE SIDEBAND TRANSMITTER

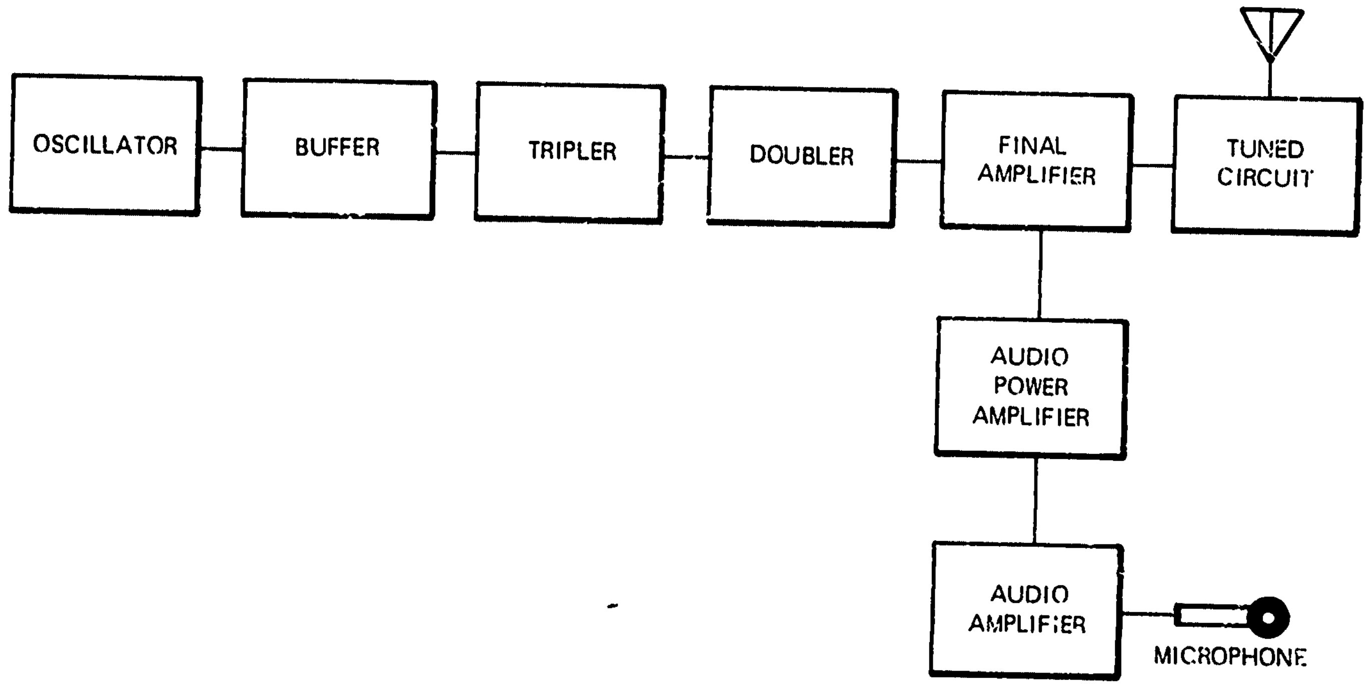


FIGURE 10-2 HYPOTHETICAL AM TRANSMITTER

The hypothetical design shown is applicable to a VHF AM transmitter operating in the 120 MHz band. The exact operating frequency is established by the oscillator, which operates nominally at 10 MHz.

The 10 MHz signal taken from the buffer stage is applied to a tripler. The tripler is a nonlinear amplifier having in its output a circuit tuned to three times the input frequency, or in this case 30 MHz. This stage is followed by a doubler of similar design. The output of the doubler is applied to the final amplifier, which itself acts as a doubler. The modulating signal is applied at the final amplifier.

The frequency multiplier scheme used in the transmitter is a relatively bad design from an EMC viewpoint. Most of the stages are nonlinear, and frequency conversion is accomplished at high level in the final amplifier. Primary functional signals occur at 10, 30, 60, and 120 MHz. Subject to the nature of interstage coupling mechanisms and shielding, oscillator products may occur in 10 MHz increments throughout the spectrum. A significant amount of power may be released from the final amplifier at frequencies of 110 and 130 MHz. The usual harmonic outputs can also be produced, in this case the fundamental is 60 MHz, and splatter can be caused by clipping on negative modulation peaks.

The above examples have illustrated that it is possible to examine an actual or tentative transmitter design, predict the frequencies at which spurious emissions can occur, and infer the character of these emissions.

Making a complete analysis of spurious signals from a given transmitter design is a long and arduous process. Moreover, in view of the complex effects of variables such as spurious coupling and shielding, it is possible to arrive at only an approximation of the spurious emission spectra.

Some communications transmitter emissions are difficult to predict and therefore cannot be anticipated adequately in the analysis. As an example, some transmitters do not use a simple oscillator as a frequency source, but rather use a frequency synthesizer. A frequency synthesizer is used where channelized transmitting frequencies are desired. It involves digital multiplication from a low frequency reference source, and employs a phase lock loop (PLL) circuit to produce the desired output frequency. Multiplication is achieved by placing a divider in the feedback loop of the PLL. Since operation is digital, the basic waveforms used in the circuit are either square or rectangular. Such waveforms are particularly high in harmonic content; and, due to the digital divider, a large number of components not harmonically related to the input frequency may also be present. The degree to which these signals are an EMC hazard depends on the integrity of transmitter shielding and the frequency response of interstage coupling and buffer circuits. This type of interference can therefore not be accurately predicted.

Another type of signal that is difficult, if not impossible, to predict is that associated with parasitic oscillations. Parasitic signals result from oscillation in the final amplifier at frequencies corresponding to stray resonances in the circuit. The most common form is high frequency oscillations occurring at peaks of the carrier waveform. This particular form of parasitic usually can be eliminated by use of a parasitic choke in the final amplifier circuit. More difficult to eliminate

is the low frequency parasitic. This signal is particularly hazardous in that it modulates the intended carrier, occurring in the form of spurious sidebands, typically, in the range of 10 to 100 kHz above and below the carrier frequency. The spurious sidebands are usually modulated themselves, with a distorted version of the intentional modulation, and as a result, occupy a finite amount of bandwidth. While the energy content of these sidebands is far less than that present in the intended signal, it is usually sufficient to jam adjacent communications channels in nearby receivers.

Non-Communications Transmitters

Non-communications transmitters consist principally of radar and countermeasures equipments, and certain types of navigation beacons. The distinction between communication and non-communication transmitters is based upon whether or not the system is used for information transmission (voice, data). With the exception of navigation beacons, the chief attribute of non-communication transmitters is high peak power level. Because of the power level involved in radar transmitters, they are an extremely serious interference hazard to any receiver or low level signal processor in close physical proximity or on an aircraft.

The radar complement of a typical aircraft includes both pulse and CW systems. The operation of pulse radar is predicated on the transmission of high level, short duration pulses, which are repeated at regular intervals. Since the duration of the pulse is extremely short with respect to the repetition period, comparatively little average power is required to develop a pulse with a high peak level. Unfortunately, the degree to which pulse radar causes interference to other systems is a function of the peak, rather than of average power.

The achievement of compatibility between radar and other aircraft systems lies in predicting the spectrum of the intended output signal, as well as spurious signals, co-siting radar and other antennas properly, and taking appropriate shielding precautions on potential victim devices. In addition to these methods, other specialized techniques have been developed. One such method involves synchronizing the pulse repetition rates of two pulse radars to reduce interference patterns on the display screen.

Another type of non-communications transmitter is the navigational beacon. This is generally a relatively low power transmitter operating in the VHF or UHF or microwave frequency. Some beacons may incorporate, in addition to continuous or tone modulation, a code that identifies the aircraft. Many beacons are transponders designed to reply to interrogation by a friendly radar, and operate on the same frequency as the radar. This type of transmitter generates interference similar to that from a communications transmitter operating in the same frequency range.

Other Functional Sources

The remaining functional sources aboard an aircraft are characterized by the fact that they are not intentional RF transmitters, but rather closed-circuit

systems using radio frequency signals for specific functional purposes. Examples of equipments that are functional sources include radar, communications, and navigation receivers. certain CRT display systems invoiving raster presentation, and certain high-speed digital equipment.

While the frequency content of the functional signal is known, it is difficult to predict interfering signal levels since a complex variety of coupling mechanisms is involved.

It is, however, possible to plan some aspects of the system to minimize interference. For example, in a single-conversion receiver, the relationship between the receiver-tuned frequency and the local oscillator is known. It is displaced from the tuned frequency by an amount equal to the IF frequency, and in most cases is above the tuned frequency. The local oscillator can be coupled back to the receiver antenna and thence into other receivers. If appropriate design factors are not continued in the system planning phase, the result may be a jammed communications channel.

Analysis and Prediction of Interference from Functional Sources

The analysis and prediction process begins with a determination of all possible spurious emission mechanisms. It will become evident that some spurious emission mechanisms are serious and difficult to eliminate with proper design, while others either are sources of negligible interference because the signal levels are low, or can readily be eliminated as a hazard through proper design. An example of an emission that cannot be eliminated is transmitter final amplifier noise. Low level frequency conversion signals can, on the other hand, be greatly reduced by proper shielding and filtering at various points in the transmitter. In a well designed transmitter, these sources are contained, and for all practical purposes, eliminated as potential hazards. Finally, the level and frequency of all intentional and important spurious signals are determined.

If the candidate communications or radar transmitter is in the design phase, emission predictions can aid in developing a transmitter that does not have spurious emission in certain critical frequency ranges. There are a large number of different frequency multiplication and conversion methods that can be used to achieve a given output frequency.

In cases involving determination of the hazard associated with using a particular transmitter nomenclature in an avionics system, prediction theory is used if no empirical data on the transmitter spurious spectra is available.

Transmitter EMC analysis is concerned with predicting the level and frequency of all intended and spurious emissions. Where modulation is used, the modulation bandwidth must be estimated. It is also important that the modulation bandwidth of the spurious signals be known. Finally, the behavior of the transmitter circuits under the influence of operator adjustment and misadjustment must be evaluated.

Harmonic Generation

Signal harmonics can be generated at any stage of the transmitter where an

intentional or nonintentional nonlinearity is encountered. An example of an intentionally nonlinear element is a frequency multiplier. All final amplifiers produce harmonics to a certain degree even if designed for linear operation. The output spectrum associated with harmonics has the general form

$$f = nf_o.$$

where

n = an integer
f_o = the fundamental frequency

Successive harmonics will decline in amplitude, the exact form or relationship depending on the design of the transmitter. Moreover, the signal amplitude of the harmonics, when observed at points to which the signal has been conducted or radiated, may not necessarily obey such a rule, since the transfer between the source and the remote point can affect the relationship.

If, for instance, the spurious harmonic is generated at an early stage of the transmitter, the amplitude at the output is a function of the coupling between all intervening transmitter stages, including both intentional and spurious paths. Similarly, the amount of a final amplifier harmonic that is radiated depends on properties of the transmission line and antenna.

Harmonics may or may not be modulated, depending on the location of the source with respect to the transmitter modulator. An example of an unmodulated harmonic would be one from the transmitter local oscillator.

The chief source of harmonics that might constitute an EMC hazard is the final amplifier of the transmitter, since this stage employs high power levels. The harmonic content of the amplifier, measured at the output, can be determined by analysis of the final amplifier operating curves. Any analysis of the final amplifier is not complete, however, unless the input spectrum to the amplifier is identified. This requires analysis of preceding stages. At no point after the first amplifier or multiplier can the spectrum be considered to consist of a single frequency.

The analysis procedure for each stage is similar and involves graphical determination of harmonic level as a function of the conduction angle of the stage at the fundamental frequency.

The analysis considers that three processes contribute to the output spectrum.

1. Amplification
2. Harmonic generation
3. Mixing

The contribution of each mechanism can be computed and the result summed up for each output frequency. For single-ended stages, the procedure involves the use of four nomographs illustrated in Figures 10-3 through 10-6.

Figure 10-3 illustrates the effect of adding signals of different levels at the same frequency. It is seen from the figure that the effect of adding two signals of

equal level is a 3 dB increase of level, while for increasing disparity of levels, the net increase resulting from addition of levels decreased rapidly, reading negligible proportions when the difference between the two signals is in excess of 10 dB. This graph will be used as an aid in summing spurious levels resulting from more than one mechanism.

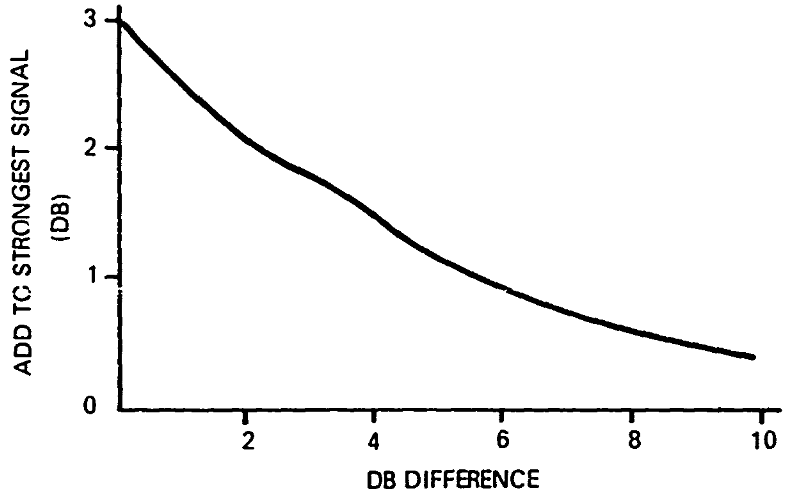


FIGURE 10-3. ADDITION OF LEVELS OF TWO SIGNALS ON THE SAME FREQUENCY

The harmonic level which theoretically results for a single-ended amplifier is shown in Figures 10-4 and 10-5. Figure 10-4 illustrates the level of the second, third, and fourth harmonics, as a function of conduction angle. The levels are expressed in dB below the fundamental. The data are given for two assumptions, which represent the extremes of what results in actual practice. The first assumption involves a linear transfer characteristic, while the second involves a squared transfer characteristic. When using the graph for prediction purposes, the higher of the two curves at any given point is used, since this constitutes a worst case.

Figure 10-5 illustrates the levels of higher harmonics as a function of conduction angle. It is extremely difficult to make reliable predictions for higher harmonics since neither the transfer characteristic nor the conduction angle can be estimated with the requisite precision. Therefore, an approximation of the worst case is made by drawing a line of maximums. Harmonics will not generally exceed this level and will usually be below it.

Figure 10-6 illustrates the response characteristic of a single tuned tank circuit for different values of Q, which covers the output network used in most amplifier circuits. It is not valid for double tuned circuits or more complex circuits, such as Butterworth and Chebyshev filters. If such filters are used, the response characteristic of the particular filter should be used.

Computation of the spurious output by use of the graphs requires knowledge of the following:

1. Input spectrum
2. Type of stage--amplifier, doubler, tripler, others
3. Conduction angle
4. Output network:
   Q if single tuned
   Response characteristic if double tuned or higher order

If the conduction angle is not known, a worst case estimate can be developed based on the type of stage. The minimum practical conduction angle for a given type of stage yields a maximum possible spurious radiation. The minimum conduction angles for various stage functions are listed below:

Stage Function	Minimum Practical Conduction Angle
Amplifier	100°
Doubler	80°
Tripler	70°
Quadrupler	60°
Quintupler	50°

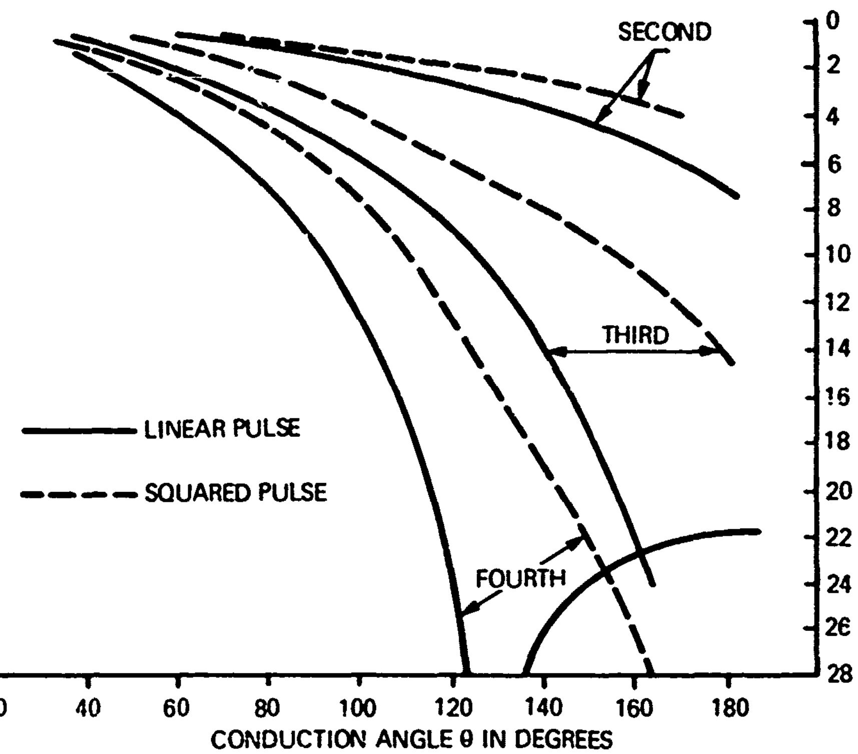


FIGURE 10-4 HARMONIC LEVELS AS A FUNCTION OF CONDUCTION ANGLE - SECOND, THIRD, AND FOURTH HARMONICS

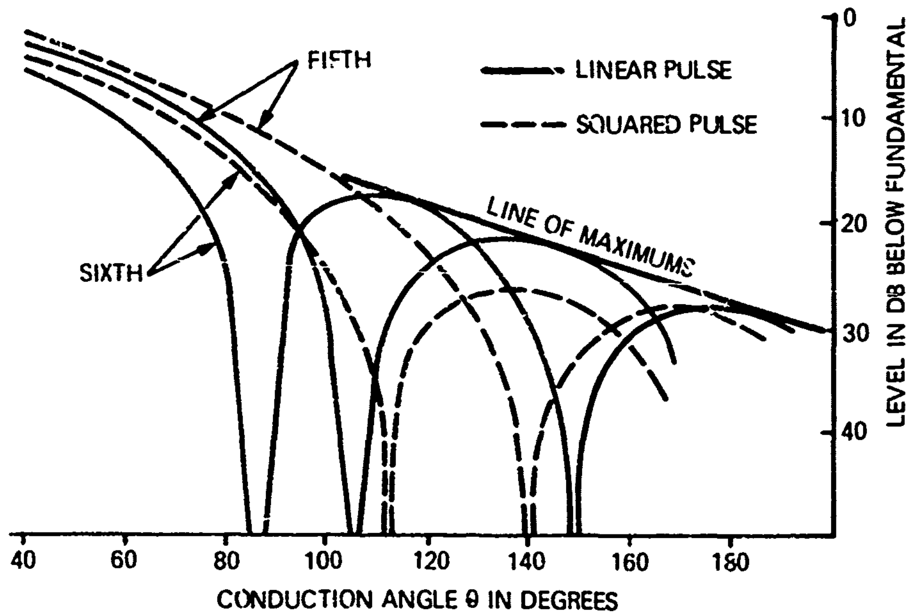


FIGURE 10-5 HARMONIC LEVELS AS A FUNCTION OF CONDUCTION LEVEL - FIFTH AND HIGHER HARMONIC

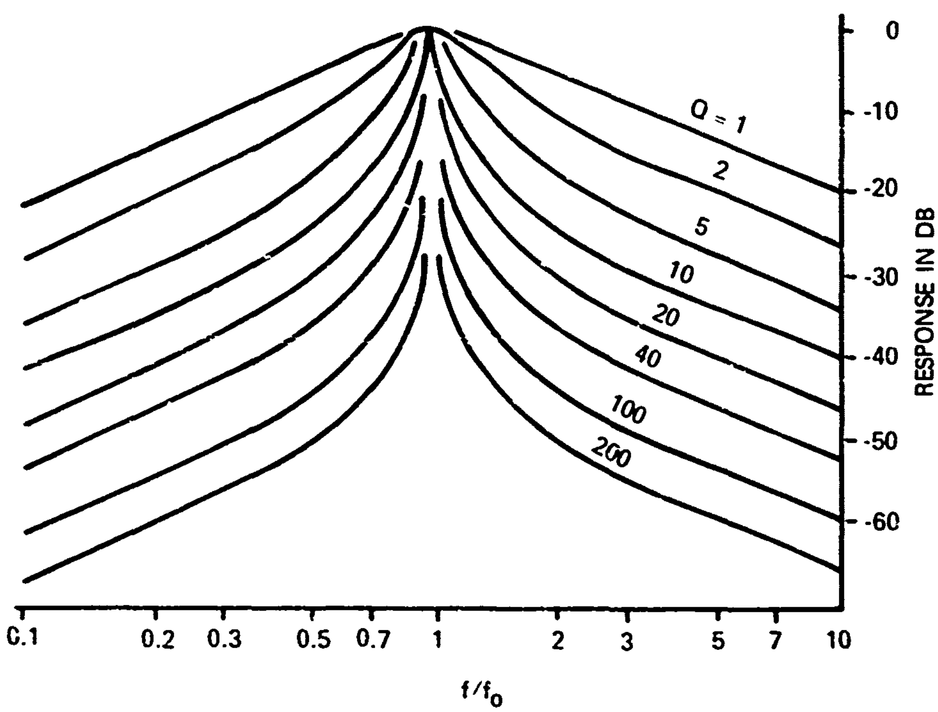


FIGURE 10-6 RESPONSE OF A SINGLE TUNED CIRCUIT

To illustrate the procedure, an analysis of a typical tripler circuit will be conducted. The analysis is best performed by constructing a table of interim results, all expressed in dB; the result is computed by adding and subtracting data entries in various columns of the Table 10-1, as applicable.

It is assumed that the tripler has a conduction angle of 100° and an output tank circuit with a Q of 20. The signal applied to the tripler circuit is assumed to come from a buffer amplifier with an output spectrum as given in Column 2.

The first operation performed on the input signal data consists of adjusting it so that it is normalized for the third harmonic. This is accomplished by entering the graph of Figure 10-4 for an angle of 100°, obtaining a 4 dB correction factor for the third harmonic. This is added to the components of Column 1 and the results entered in Column 3.

TABLE 10-1. INTERIM RESULT FOR ANALYSIS OF TYPICAL TRIPLER CIRCUIT

1	2	3	4	5	6	7	8	9	10	11
Input Spectrum Component f/f_1	Input Component Level (dB)	Plate Current Transfer Level (dB)	Plate Current Harmonic Level (dB)	Stronger of 3 or 4 Plus Adjustment	Mixing Components	Product Level (Weaker Component -11 dB)	Add to Stronger Signal (dB)	Plate Current Spectrum (Stronger of 5 or 7, +8)	Plate Circuit Response	Output Spectrum
1	0	4		4				4	-36	-32
2	-13	-9	2	2				2	-31	-29
3	-26	-22	0	0	2+1	-20	0	0	0	0
4	-38	-34	-4	-4				-4	-21	-25
5			-11	-11	3+2	-32	0	-11	-28	-39
6			-19	-19				-19	-31	-50

The data in Column 3 are then operated on, using Figures 4 and 5 as applicable to produce the harmonic levels indicated in Column 4.

In Column 5, the values of Columns 3 and 4 are added together using Figure 10-3. This entails taking the larger of the two values and adding to it the adjustment factor given in Figure 10-3. Where the difference between Columns 3 and 4 is greater than 10 dB, no adjustment factor is used.

Column 6 lists possible mixing components that contribute to harmonic levels. Only components whose levels in Column 3 are equal to or greater than the values of Column 3 or 4 for the frequency considered, are noted. In the case cited, only two such products exist, namely, frequency 3 can be produced by mixing 2 and 1, while frequency 5 can be produced by mixing 3 and 2.

In Column 7, the product level is tabulated. It is assumed that the worst case conversion loss is 11 dB, that is, the product level is 11 dB less than the weaker of the two components as given in Column 5. These levels are then added to the components of Column 5 using Figure 10-3 as listed in Column 8. The computed result is listed in Column 9. This column gives the level of each harmonic component before filtering.

Column 10 gives the filter transfer characteristic for each component. In the example given, it was assumed that the output filter is a single tuned circuit having a Q of 20. The values in the column were obtained from Figure 10-6.

The factors given in Column 10 are added to the component levels of Column 9 to produce the output results listed in Column 11.

A complete analysis using the above method must begin at the first stage of the transmitter, and be repeated for each stage using the results obtained for the preceding stage. Where the transmitter involves mixers, the technique can be modified by using the conversion gain of the intentional mixer rather than -11 dB in computing Column 7. When the analysis is complete, the final column of the table for the last amplifier will give the theoretical output spectrum into a constant load, expressed in dB referred to the level of the intended output component.

The theoretical radiated spectrum, however, may be different because of antenna effects. Most antennas present a matched impedance only at the intended frequency, and may be highly reactive at other frequencies. A common basic form of antenna, the halfwave dipole, enters a resonant condition only on odd harmonics, and presents a considerable impedance mismatch on even harmonics. Thus a dipole antenna would tend to attenuate even numbered harmonics of output fundamental, while having relatively low loss on odd harmonics.

Modulation Envelope in Frequency Domain

In the paragraph above on Harmonic Generation, a method for predicting spurious output levels was given. The analysis produced the theoretical amplitude of output spectral components. It did not, however, identify the modulation bandwidth of the components. In this section, the discussion will center on a method of computing the bandwidth of modulation components based on the type of modulation used and the characteristics of the modulating signal.

The principal forms of modulation used in communications and noncommunications transmitters involve various types of amplitude and frequency modulation. The bandwidth of the modulated signal is the primary factor determining interchannel spacing assignments in communication circuits. In narrowband systems, if high quality communications is desired, modulating components from other transmitters must not appear within the channel bandwidth of the victim system. This applies equally to both intentional modulation components and spurious components.

The simplest type of modulation, from the viewpoint of analysis, is amplitude modulation. The spectrum generated by amplitude modulation normally consists of a carrier and two sidebands above and below the carrier frequency.

Even a perfect square law modulator, however, produces additional products. In general, the products include secondary and tertiary distortion of the modulating signal; secondary and tertiary distortion of the carrier; second order modulation of the carrier; and first order modulation of the carrier second harmonic.

If the carrier is modulated with a single frequency, the total spectrum might appear as in Figure 10-7. It consists of the modulating signal and its second and third harmonics, and modulated and unmodulated versions of the carrier and its harmonics. The fundamental carrier has both primary and secondary sidebands. The primary sidebands are at frequencies equal to the sum and difference between the modulation signal and the carrier, while the secondary components are at frequencies equal to the sum and difference between the carrier and twice the modulation frequency. The second harmonic of the carrier is modulated only in the first order mode, and the third harmonic is unmodulated. In addition to the products shown, other higher order components are possible. For practical purposes, however, these components are of negligible amplitude when compared to the carrier.

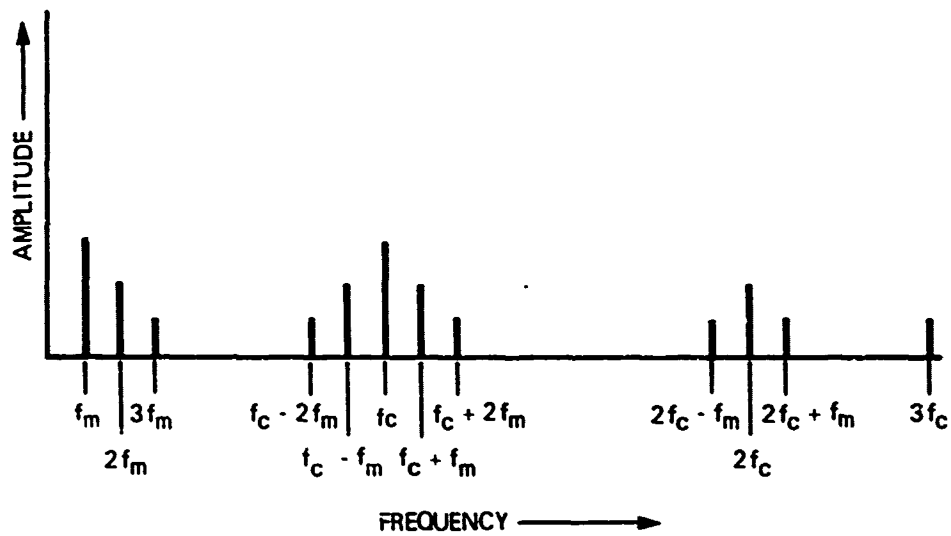


FIGURE 10-7 SPECTRUM OF AMPLITUDE MODULATED CARRIERS

In virtually all modulators, a filter is used to reduce and eliminate all but the primary modulation components. The modulated signal, therefore, takes on the appearance of a carrier with an additional frequency above and below it. When the carrier is modulated by complex waveforms, the result is a carrier and two sidebands. The bandwidth of each sideband is equal to that of the modulation signal, and the modulation spectra will, in consequence, resemble the double sided spectra of the baseband signal. Thus, the modulation spectrum can be found by Fourier Analysis of the baseband signal. Methods of Fourier Analysis are discussed in the next section.

In an ideal AM modulator operating at 100 percent modulation, the power contained in each of the two sidebands is 1/4 that of the carrier. The fact that all the modulation signal information is contained in one of the two sidebands led to the development of the signal sideband transmission system presently used for voice communications in the HF band. The advantage of the system is that less power is needed and the bandwidth allocated for the communications channel is effectively cut in half. A typical single sideband transmitter suppresses the carrier through use of a balanced modulator and removes the undesired sideband with a filter. Although the carrier and unwanted sideband suppression is typically about 60 to 70 dB, sufficient level may be present to preclude the use of the adjacent channel if the transmitter power is high.

Frequency modulation is considerably more difficult to analyze than amplitude modulation. In frequency modulation, the frequency of the wave is varied in proportion to the amplitude of the modulating signal. The character of the spectrum that results is strongly dependent on the modulation index, which is given by

$$\beta = \frac{\Delta f}{f_1} \tag{10-1}$$

where Δf is the frequency deviation and f_1 is the modulating frequency.

In the case where $\beta < 0.5$, the spectral characteristics of frequency modulation are quite similar to that of amplitude modulation. For example, for a single modulating frequency, the emission consists of the carrier frequency and components at frequencies equal to the sum and difference between the carrier and modulating frequencies. The spectrum differs, however, from that of amplitude modulation because the side frequency components are antiphasic: one component is negative with respect to the other. The channel bandwidth necessary for such a narrowband FM signal closely approximates that of a DSB AM channel.

Because a significant increase in signal to noise ratio when compared to AM systems does not occur unless $\beta > 0.5$, many FM systems use what is known as wideband modulation. This term is applied because the spectrum for single frequency modulation no longer consists of a carrier and a single pair of side frequencies. Rather, the spectrum contains a multitude of side frequencies located at multiples of the difference frequency above and below the carrier. In theory,

the extent of the spectrum is infinite; however, in practice it has become the convention to consider only components that have an amplitude equal to more than 1 percent of the unmodulated carrier level as being a hazard to nearby receivers. The amplitude of each pair of spectral components is given as a function of the modulation index by successive orders of Bessel functions.

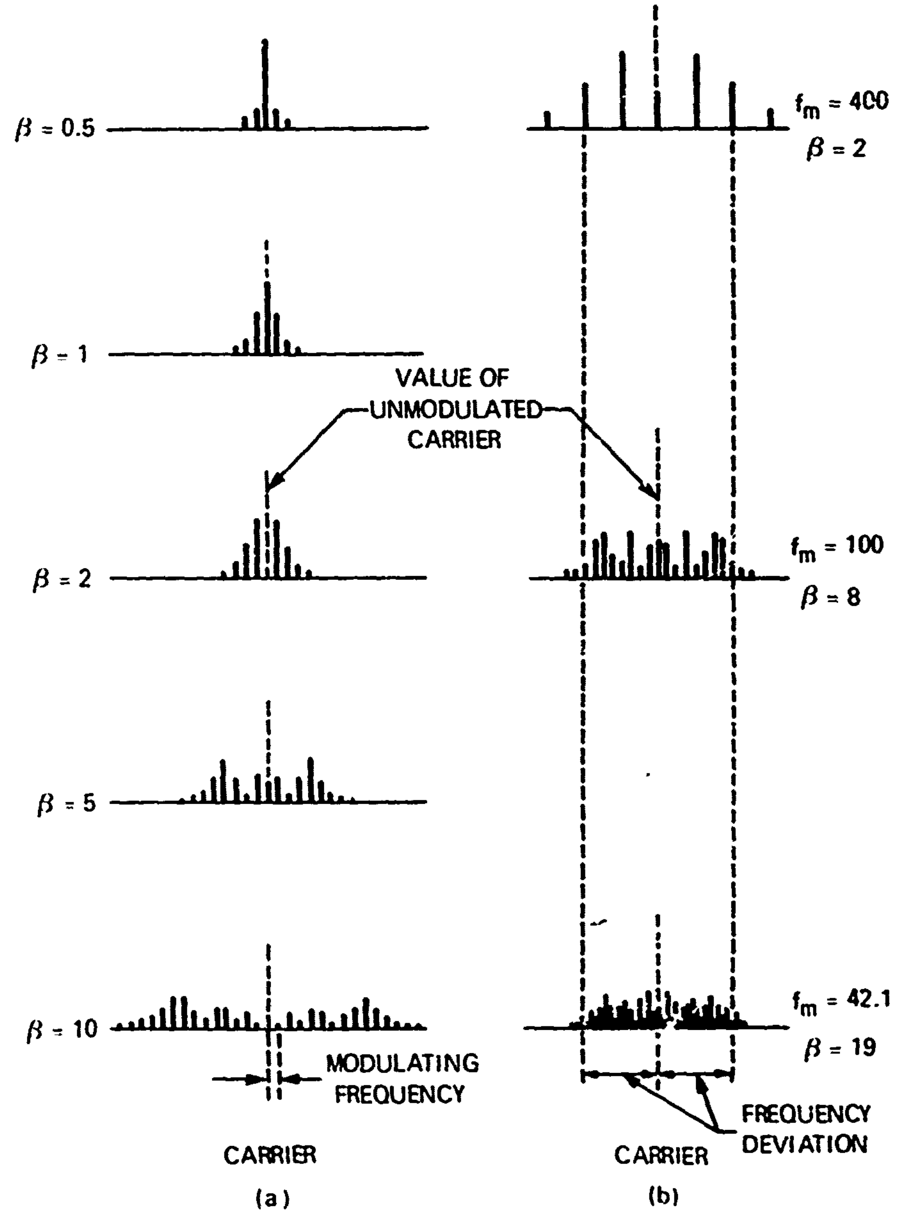


FIGURE 10-8 THE FREQUENCY SPECTRUM OF A FREQUENCY-MODULATED WAVE: (a) AS A FUNCTION OF THE MODULATING VOLTAGE, AND (b) AS A FUNCTION OF THE MODULATING FREQUENCY

Several modulation spectra are illustrated in Figure 10-8. Figure 8(a) illustrates the effect of modulation index on the spectra, while Figure 8(b) illustrates the effect of modulation frequency for constant modulating signal amplitude (constant frequency deviation). In this illustration, only components having amplitudes in excess of 10 percent of the unmodulated carrier are shown. This convention is that generally used to compute required channel bandwidth. The number of pairs of such significant components is one in excess of the modulation index, when the index is an integral quantity. The bandwidth required is essentially proportional to the modulation index, which in turn is dependent on the amplitude of the modulating signal. If the carrier amplitude is held constant, the bandwidth requirement exhibits little variation with modulating signal frequency. Note that the bandwidth is always in excess of the total frequency deviation.

Figure 10-9 illustrates the relationship between modulation index and bandwidth. Two curves are shown on the graph. The upper curve delineates the bandwidth, which includes all components that are 1 percent or more of the unmodulated carrier in amplitude. The lower of the two curves delineates the bandwidth, which includes all components that are 10 percent or more of the unmodulated carrier in amplitude.

The graph may be used to compute the expected channel bandwidth of a communications system. For example, if the highest modulation frequency is 4 kHz (a typical voice channel) and the design maximum frequency deviation is ±12 kHz with respect to the carrier frequency, the modulation index at this frequency is 12/4 or 3. Referring to the graph, the bandwidth including all components, the levels of which exceed 1 percent of the unmodulated carrier amplitude, is twelve times the modulating frequency or 48 kHz. The bandwidth containing components in excess of 10 percent of the unmodulated carrier amplitude is 32 kHz.

This latter figure represents that usually accepted as the required channel bandwidth, while the former represents the bandwidth in which the components are usually strong enough to cause interference in nearby receivers. It must be recognized, however, that the potential interference bandwidth increases in proportion to the transmitter power since the modulation components are fixed percentages of the unmodulated carrier level. The approach to this problem in a systems design involving a hierarchy of FM transmitters and receivers involves assignment of one or more empty, or guard, channels between transmitting frequencies to protect a receiver on one channel from interference from a transmitter on the nearest assigned frequency. The criteria used in the assignment scheme include both the transmitter power, and its proximity to the victim receiver. With respect to receiving and transmitting systems aboard a single aircraft, a primary ingredient in the analysis would be the amount of transmitter energy coupled into the antenna used for the simultaneously operating receiver. This coupling could conceivably be so great as to preclude operation in the same communications band.

In defining the parameters of an FM communications system, the transmitter is assigned a particular maximum frequency deviation. Modulation is

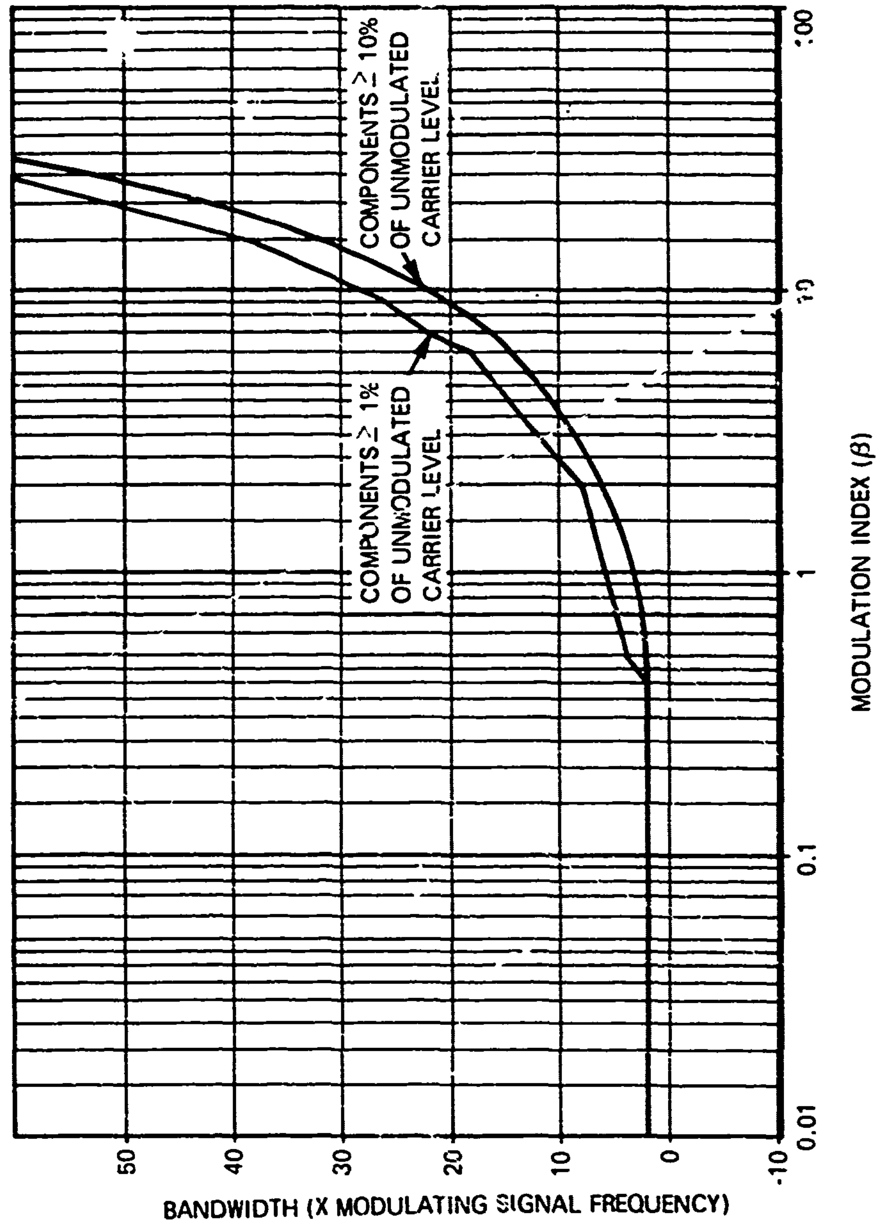


FIGURE 10-9 RELATIONSHIP BETWEEN MODULATION INDEX AND BANDWIDTH FOR FREQUENCY MODULATION

then expressed as a percentage of the maximum deviation. It follows from this that the modulation index of a 100 percent modulated signal is not constant, but is inversely proportional to the modulating signal frequency. The effect of this is that analysis of the modulation spectrum becomes quite involved when the modulating signal is a complex waveform. In the frequency modulation case, the modulated wave must be subjected to Fourier Analysis to develop the spectrum distribution. This differs considerably from amplitude modulation where it was only necessary to subject the modulating waveform to Fourier Analysis.

Fourier Analysis of a modulated FM signal is extremely tedious and difficult. Fortunately, it is not generally necessary where systems channel assignments are being computed unless special circumstances require detailed knowledge of the distribution.

Figure 10-10 illustrates some typical spectra that result from nonsinusoidal repetitive modulation waveforms for relatively high modulation indices. The spectra illustrate the general rule that the longer an FM wave remains in a certain range of frequencies, the greater will be the spectral contribution in that frequency range.

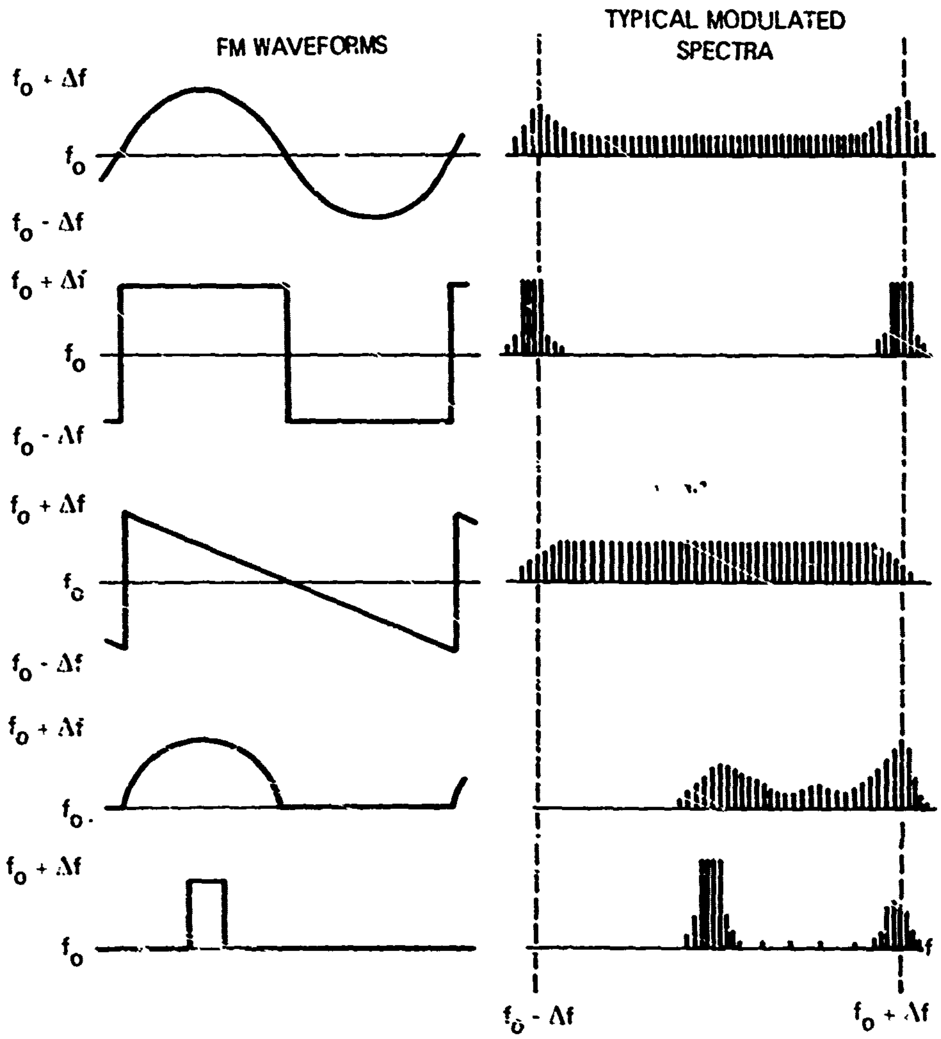


FIGURE 10-10 FM WAVEFORMS AND CORRESPONDING TYPICAL MODULATION SPECTRA

Complex Waveform Analysis

Although all potentially interfering signals can be thought of as functions of amplitude versus time, each can also be equivalently expressed as a function of amplitude versus frequency. Often, attenuation and other propagation phenomena between the emission source and victim device are different for different frequency components of the EMI. Most significantly, the response of many devices to interfering energy is a function of frequency.

Therefore, it is theoretically much more useful to consider the interfering signals in the frequency domain rather than in the time domain. For periodic signals, the relationship between the time representation and the frequency representation is obtained by means of a Fourier series:

$$f(t) = \frac{1}{2}a_o + \sum_{n=1}^{\infty}(a_n \cos n\omega_o t + b_n \sin n\omega_o t) \qquad (10\text{-}2)$$

where

t = time

f(t) = signal amplitude as a function of time.

n = a summing index, which successively assumes all values between 1 and ∞.

ω_o = basic frequency (in radians per second) with which the signal repeats itself, i.e., the periodic frequency.

$$a_n = \frac{1}{\pi}\int_o^{2\pi} f(t) \cos (n\omega_o t)\, d(\omega_o t)$$

$$b_n = \frac{1}{\pi}\int_o^{2\pi} f(t) \sin (n\omega_o t)\, d(\omega_o t)$$

From this, it can be seen that periodic functions of time, no matter how complex, can be represented as the summation of a large number of frequency components, each of which is harmonically related to a fundamental frequency.

When dealing with a nonperiodic impulse or random signal, the representation in the frequency domain no longer consists of a succession of discrete frequency components but becomes a continuous function of frequency. For the continuous case, the Fourier integral establishes the relationship between the interfering signal amplitude as a function of time and the interfering signal amplitude as a function of frequency.

$$g(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} f(t)\, e^{-j\omega t}\, dt \tag{10-3}$$

where:

$g(\omega)$ = signal amplitude as a function of frequency

$f(t)$ = signal amplitude as a function of time

t = time

e = natural logarithm base (2.718 ...)

j = $\sqrt{-1}$

ω = frequency in radians per second

The faster a signal changes with time, the higher the significant frequency components that must be considered. A DC level that does not change with time has no frequency components, whereas near the other extreme, an ideal rectangular wave that changes nearly instantaneously from zero to some nonzero amplitude has an extremely large number of significant frequency components.

An example of the operation of a Fourier transformation, for the application of the analysis to a periodic train of rectangular wave pulses, is shown in Figure 10-11. After performing the required mathematical manipulation defined by the methods of a Fourier Analysis, the following expression is obtained for the signal amplitude (voltage or current) level existing at discrete frequencies generated by the rectangular pulse train:

$$F(t) = \sum_{n=-\infty}^{+\infty} \frac{A}{k} \frac{\sin(n\pi/k)}{(n\pi/k)}\, e^{jn\omega_1 t} \tag{10-4}$$

where:

A = amplitude of rectangular pulse

n = harmonic number of the fundamental frequency

k = ratio of repetition rate to the duration time of each pulse

$\omega_1 = 2\pi f_1$

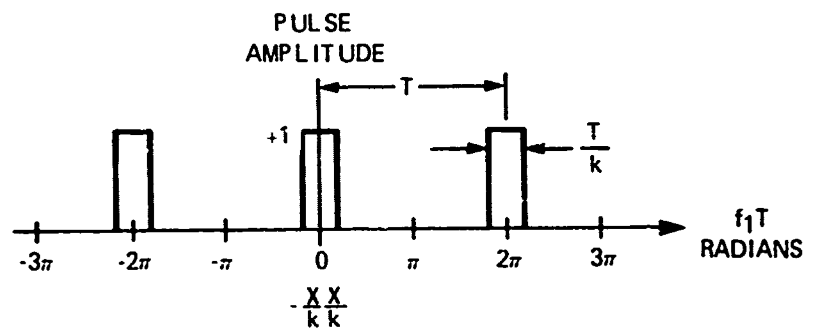
f_1 = pulse repetition rate

t = time

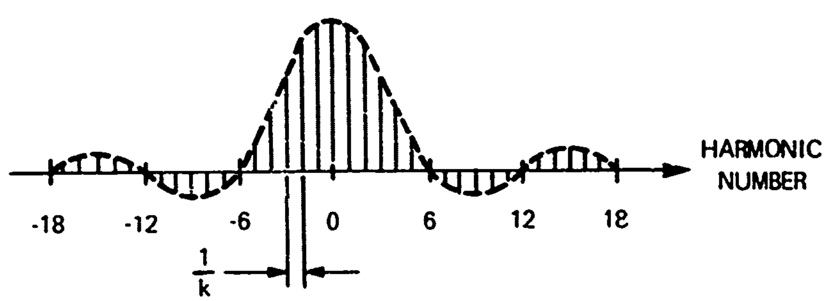
j = $\sqrt{-1}$

Equation 10-4 shows that the pulse train actually consists of an infinite number of discrete frequency components, whose amplitudes depend on the pulse duration, repetition rate, and the current or voltage amplitude of the time-varying pulses. Figure 10-11 depicts the frequency spectrum of the pulse train and its relative amplitudes. Each vertical line of Figure 10-11 represents a discrete harmonic of the fundamental frequency. The characteristic groups of spectra are sometimes called "modulation sidelobes."

Any signal that varies arbitrarily with time can be shown by the Fourier Analysis to be composed of discrete frequency components. In the case of an impulse type signal, the frequencies may take on all possible values, and therefore the energy spectrum can be found through the use of the Fourier integral (Equation 10-3). Figure 10-12 illustrates several basic signal strength variations with time and their respective frequency spectra as obtained by the Fourier transform method.



a. RECTANGULAR PULSE TRAIN (PERIOD = T)



b. FREQUENCY SPECTRUM FOR RECTANGULAR PULSE TRAIN (k = 6)

FIGURE 10-11 SPECTRAL ANALYSIS OF RECTANGULAR PULSE TRAIN

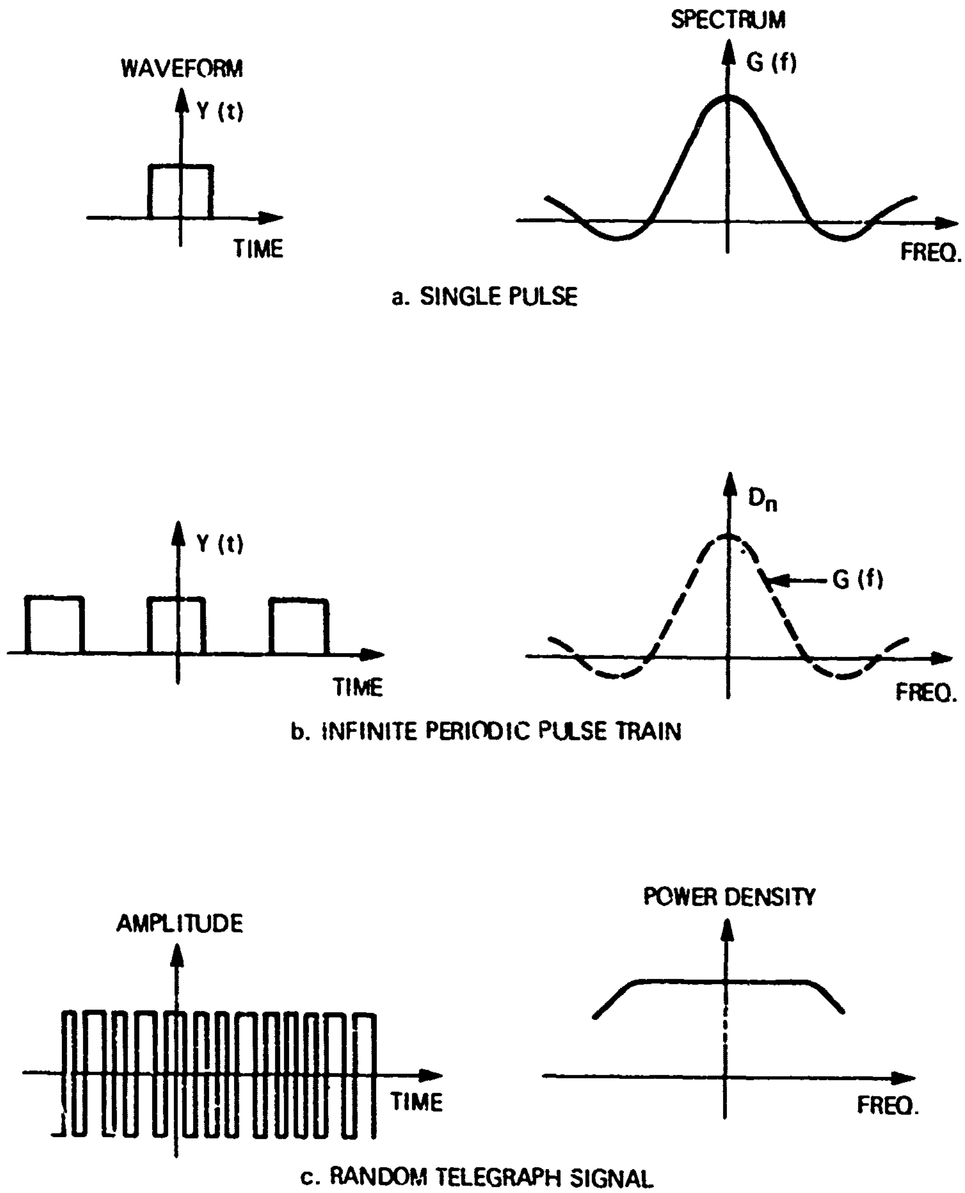


FIGURE 10-12 FREQUENCY SPECTRA FOR SEVERAL SIGNAL WAVEFORMS

Within a given aircraft system, a unit of electrical or electronic equipment may generate high RF interference that appears to be completely unrelated to anything in the electrical circuits of the equipment. For example, a simple transformer-rectifier power supply that uses only solid state rectifiers, has no moving parts, and which apparently contains no frequencies other than the power of 400 Hz, may generate interference in the megahertz region. A designer might object to the statement that his power supply is generating a pulse train, but whenever his equipment rectifies, a waveform is developed that is no longer sinusoidal but which is instead made up of sinusoidal pulses plus switching spikes resulting from charge storage in the diodes. Any waveform other than a pure, continuous sine wave contains harmonics of its repetition frequency.

Other nonfunctional equipments, such as aircraft control sequencers, data systems, and computers, generate serial pulse waveforms ranging from audio to radio-frequency repetition rates. These waveforms are simply limiting forms of rectangular pulse trains for which the opposite limiting form is the impulse train. A study of a square-wave train in some detail will give valuable insight into the analysis of nonsinusoidal waveforms in general. The following expressions will be used in the succeeding discussion.

T = waveform repetition period in microseconds

t = time duration in microseconds of all or a specified part of the pulse

A = pulse amplitude in volts

Amplitude, time duration, and repetition rate supply all the waveform information necessary to predict the amplitude envelope versus frequency of the interference spectrum; that is, to predict the interference amplitude at each specific harmonic frequency of the pulse waveform.

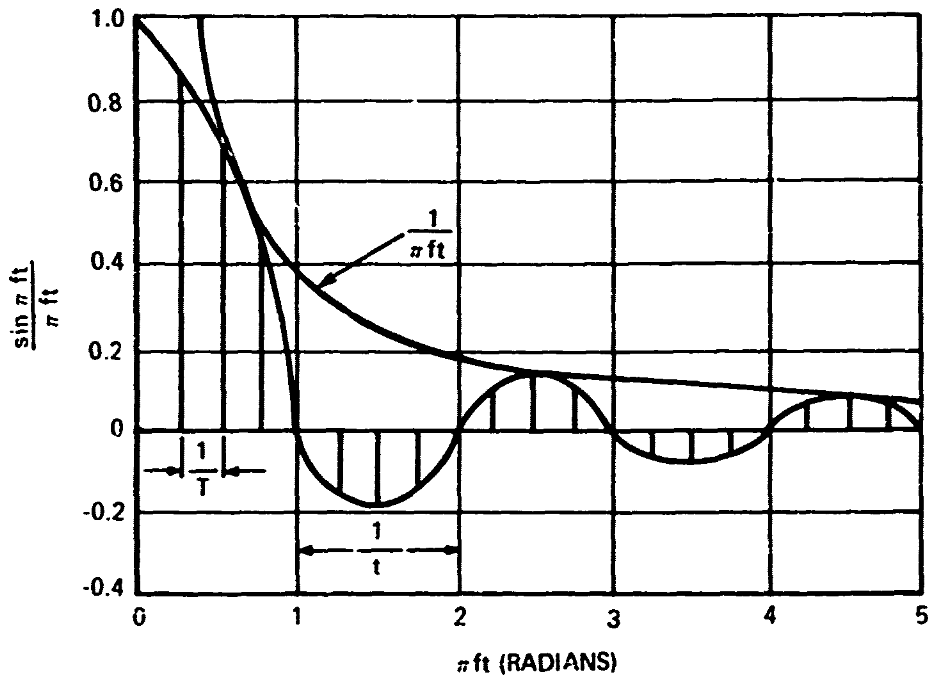
Figure 10-13 is a plot of the normalized function

$$\frac{\sin \pi ft}{\pi ft} \tag{10-5}$$

with the independent variable π ft. Also shown is a plot of the function $1/\pi$ ft, which is tangent to the maximum values of the trigonometric function. This graph shows the distribution of individual harmonic amplitudes as well as the envelope of the maximum harmonic amplitudes for the square wave. The uniformly spaced vertical lines indicate individual harmonic responses of a rectangular pulse train or a square wave with an amplitude of unity, a repetition period T, and a pulse width t. The spectral lines are separated by a frequency of 1/T (the pulse repetition frequency). The width of each of the lobes of the spectral distribution, that is, the spacing between zero points, is 1/t. This frequency corresponds to the reciprocal of the pulse width in microseconds if the frequency is expressed in megahertz.

Any nonsinusoidal waveform may be analyzed by the methods of Fourier Analysis into an infinite series of sinusoidal waveforms that can be added together point by point to recreate the original waveform.

If the nonsinusoidal waveform being analyzed does not have an average amplitude of zero over a complete cycle, there will also be a direct-current component $a_1/2$ which must be added to the amplitudes of the series of sinusoidal waves.



NOTE: VERTICAL LINES SHOW HARMONIC AMPLITUDES OF A PULSE TRAIN WITH A REPETITION PERIOD T, PULSE WIDTH t, AND UNIT AMPLITUDE.

FIGURE 10-13 PLOT OF FUNCTIONS $\frac{\sin \pi ft}{\pi ft}$ AND $\frac{1}{\pi ft}$

Any repetitive waveform, regardless of how complicated, may be analyzed into its harmonic components by either of two methods based on Fourier Analysis. The first method requires an analytical statement of the waveform. This analytic expression is then operated upon mathematically to derive a Fourier series that gives the amplitude of each harmonic. The second method is to plot the waveform to scale on a graph and to perform the mathematical analysis graphically. If the waveform cannot be expressed adequately by any known analytical expression, the graphical method must be used, but this method is extremely tedious and time-consuming unless an electronic computer is used. For interference prediction, sufficient accuracy can usually be obtained by using approximate mathematical expressions of the waveform amplitude versus time to provide reasonably good approximations of the harmonic coefficients.

If either of the two Fourier Analysis methods is used to analyze a square wave, the resulting coefficients of the harmonics will be the same as those shown by the vertical lines in Figure 10-13 in relation to the fundamental. A smooth curve joining the amplitudes of the harmonics will form the (sin x)x function as shown in Figure 10-13. This function is called the harmonic-amplitude envelope. Finally, a smooth curve joining the maximum amplitudes

within each lobe will form the curve 1/x indicated by the top curve in Figure 10-13. It is called the maximum-amplitude envelope.

There may be some doubt as to the physical reality of the individual frequencies shown by a Fourier Analysis, but a receiver excited by any non-sinusoidal waveform will respond exactly as if each of the frequencies exists. Thus, the question of the existence of individual spectral lines is purely academic. If a receiver of sufficiently narrow bandwidth could be used to include only one spectral line at a time, the receiver would indeed respond at the frequencies shown in Figure 10-13 and would not respond between these frequencies.

Because a pulse or impulse function generates broadband interference, the peak response function of a standard interference receiver is used to measure the interference from such a waveform. The peak function produces a response proportional to the bandwidth at the tuning frequency and is therefore the combined effect of all spectral lines falling within the tuned bandwidth. Note that the spacing between the spectral lines is the inverse of the repetition period of the pulse. Thus, there will be more spectral lines within the receiver bandwidth as the pulse repetition period becomes less.

Primary interest is in predicting the extent to which a non-functional interference source meets, or fails to meet, the requirements of a given specification given in terms of the units measured by a standard interference measurement instrument. The individual amplitudes of the harmonics generated by the interference source need not be known. All that is needed is the ability to predict the maximum amplitude envelope of the waveform being generated. This greatly simplifies the prediction problem, because the analytical expression for the harmonics can be reduced to a new expression that shows only the maximum-amplitude, within certain frequency increments. This analysis is begun by defining a simple mathematical expression that is a reasonably close approximation of the waveform under study. The Fourier Analysis of this expression can then be derived, if necessary, or the expression can be worked out from tables in a handbook. The expression will always contain one or more frequency functions that determine the maximum-amplitude envelope. Only the slope or curvature of the individual frequency functions and the amplitude of the fundamental frequency need be found to provide a starting point for predicting the maximum-amplitude envelope.

Figure 10-14 provides a tabulation of waveforms and their corresponding maximum harmonic-amplitude envelopes expressed in logarthmic form for convenience. This tabulation can be used with the charts of Figures 10-15 through 10-21 to predict the approximate response of the broadband interference receiver at any frequency of interest. If a particular waveform is not described by any of the waveforms shown in the chart, it may be approximated by some combination of the waveforms, or an expression may be worked out by using the mathematical techniques of Fourier Analysis. The harmonic envelope expressions have been given in logarithmic form because this form almost always produces a straight line or a combination of straight-line curves when plotted on semi-logarithmic graph paper. All the pulse waveforms shown and most other

pulse waveforms will produce a maximum-amplitude envelope that is a straight line with a zero slope at low frequencies, a straight line with a slope of some integral multiple of −20 decibels per decade at higher frequencies, and sometimes a second straight line sloping at a steeper rate which is an integral multiple of −20 decibels per decade.

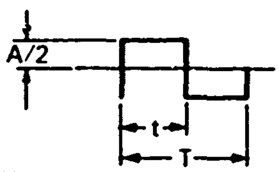
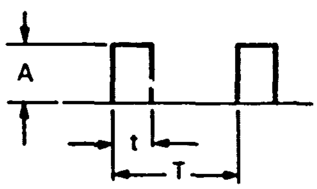
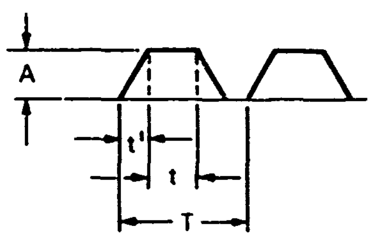
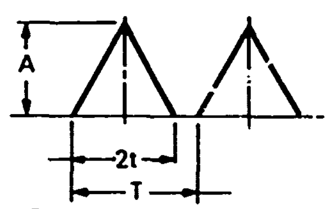
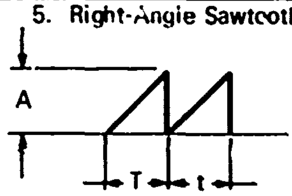
WAVEFORMS A = VOLTS t, T = SEC	HARMONIC ENVELOPE DB ABOVE 1 v/MHZ f = MHz
1. Symmetrical Square Wave  	Low Frequency $v = 126 + 20 \log At$ High Frequency $v = 116 + 20 \log A - 20 \log f$ Refer to Chart on Figure 10-5
2. Rectangular Wave  	Low Frequency $v = 126 + 20 \log At$ High Frequency $v = 116 + 20 \log A - 20 \log f$ Refer to Chart on Figure 10-5
3. Symmetrical Trapezoid  	Low Frequency $v = 126 + 20 \log A (t + t')$ Intermediate Frequency $v = 116 + 20 \log A - 20 \log f$ High Frequency $v = 106 + 20 \log \frac{A}{t'} - 40 \log f$ Refer to Chart on Figure 10-8
4. Symmetrical Triangle  	Low Frequency $v = 126 + 20 \log At$ High Frequency $v = 106 + 20 \log \frac{A}{t} - 40 \log f$ Refer to Chart on Figure 10-6
5. Right-Angle Sawtooth  	Low Frequency $v = 110 + 20 \log At$ High Frequency $v = 110 + 20 \log A - 20 \log f$ Refer to Chart on Figure 10-9

FIGURE 10-14 HARMONIC ENVELOPES OF SOME COMMON WAVEFORMS

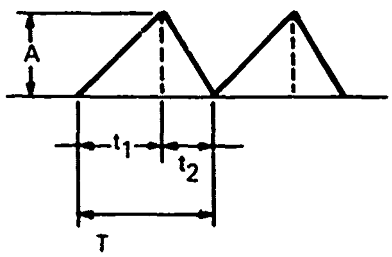
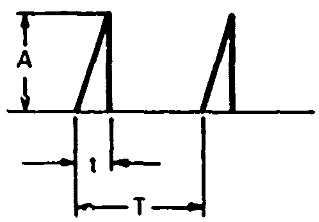
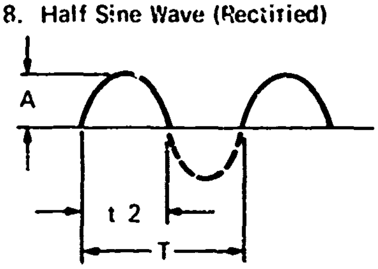
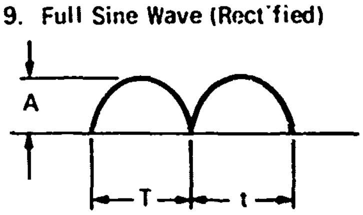
WAVEFORMS A = VOLTS t, T = SEC	HARMONIC ENVELOPE DB ABOVE 1 v MHZ f = MHz
6. Sawtooth  	Low Frequency $v = 110 + 20 \log A (t_1 + t_2)$ Intermediate Frequency $v = 110 + 20 \log A \frac{(t_1 + t_2)}{t_2} - 20 \log f$ High Frequency $v = 100 + 20 \log A \frac{(t_1 + t_2)}{t_1 t_2} - 40 \log f$ Refer to Chart on Figure 10-7
7. Clipped Sawtooth  	Low Frequency $v = 113 + 20 \log At$ High Frequency $v = 110 + 20 \log \frac{A}{t} - 20 \log f$ Refer to Chart on Figure 10-10
8. Half Sine Wave (Rectified)  	Low Frequency $v = 106 + 20 \log At$ High Frequency $v = 104 + 20 \log \frac{A}{t} - 40 \log f$ Refer to Chart on Figure 10-11
9. Full Sine Wave (Rectified)  	Low Frequency $v = 112 + \log At$ High Frequency $v = 110 + 20 \log \frac{A}{t} - 40 \log f$ Refer to Chart on Figure 10-11

FIGURE 10-14. HARMONIC ENVELOPES OF SOME COMMON WAVEFORMS (CONT)

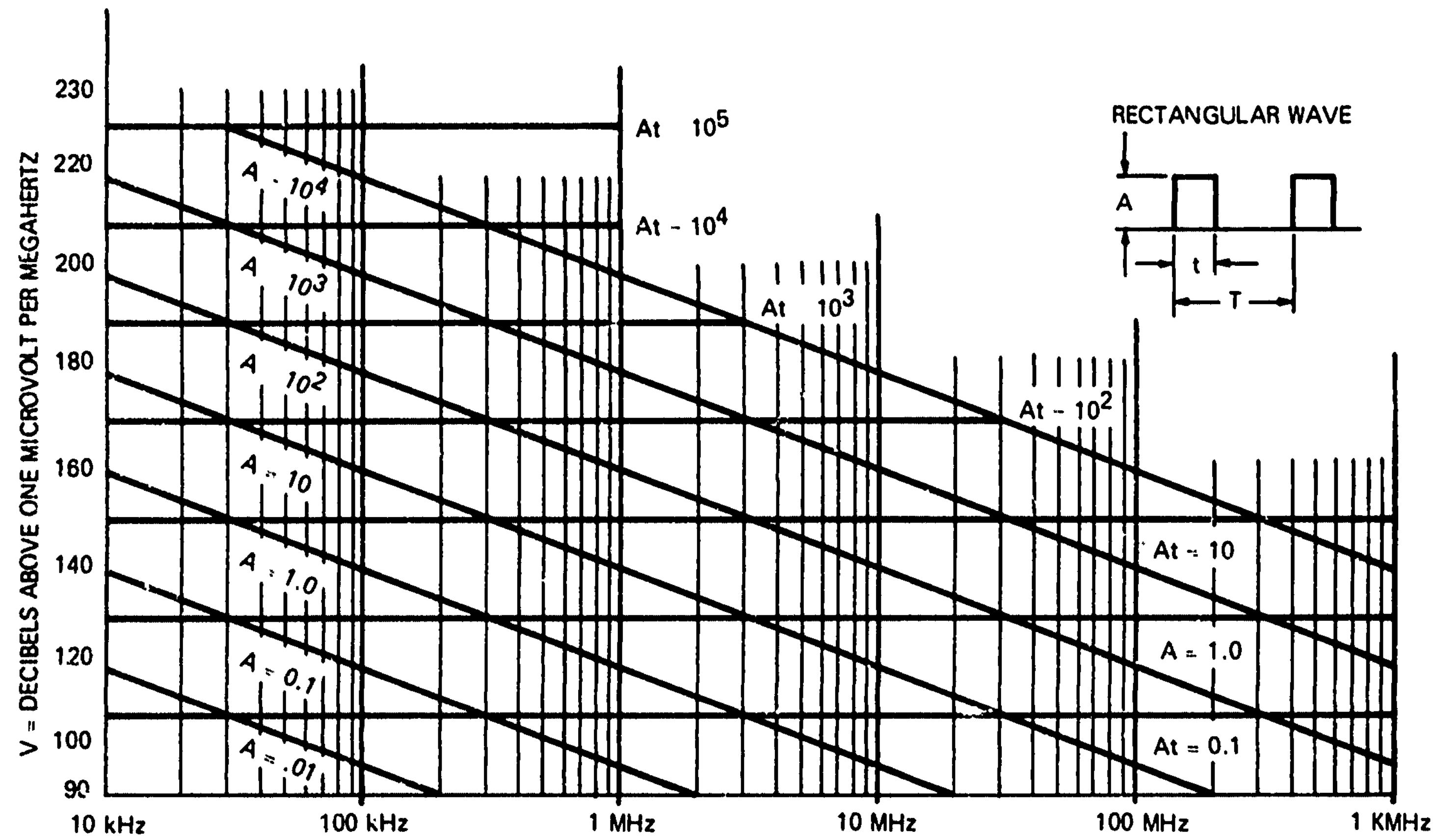


FIGURE 10-15 CONDUCTED INTERFERENCE FROM A RECTANGULAR PULSE OR PULSE TRAIN

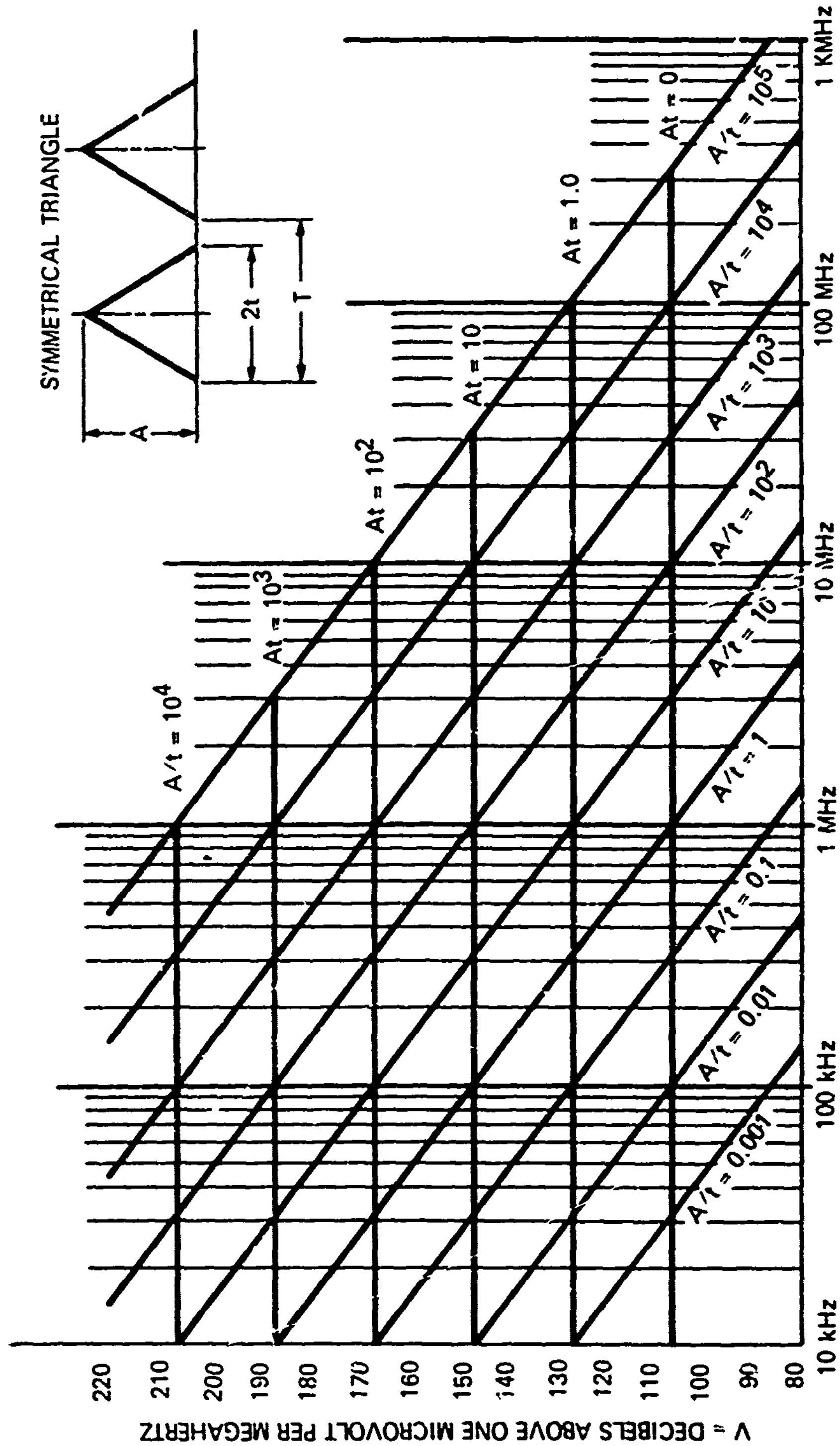


FIGURE 10-16 CONDUCTED INTERFERENCE FROM SYMMETRICAL TRIANGLE

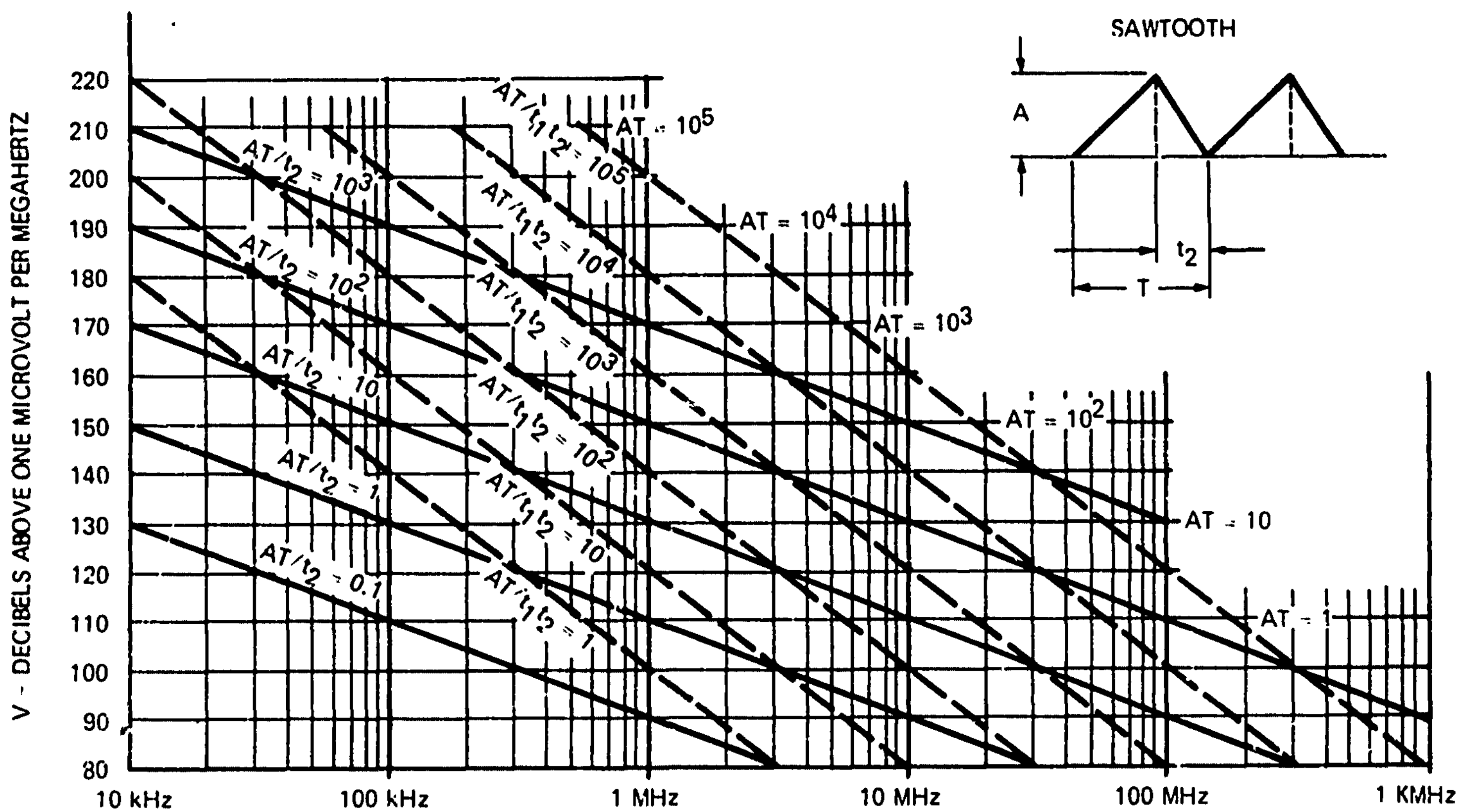


FIGURE 10-17 CONDUCTED INTERFERENCE FROM SAWTOOTH

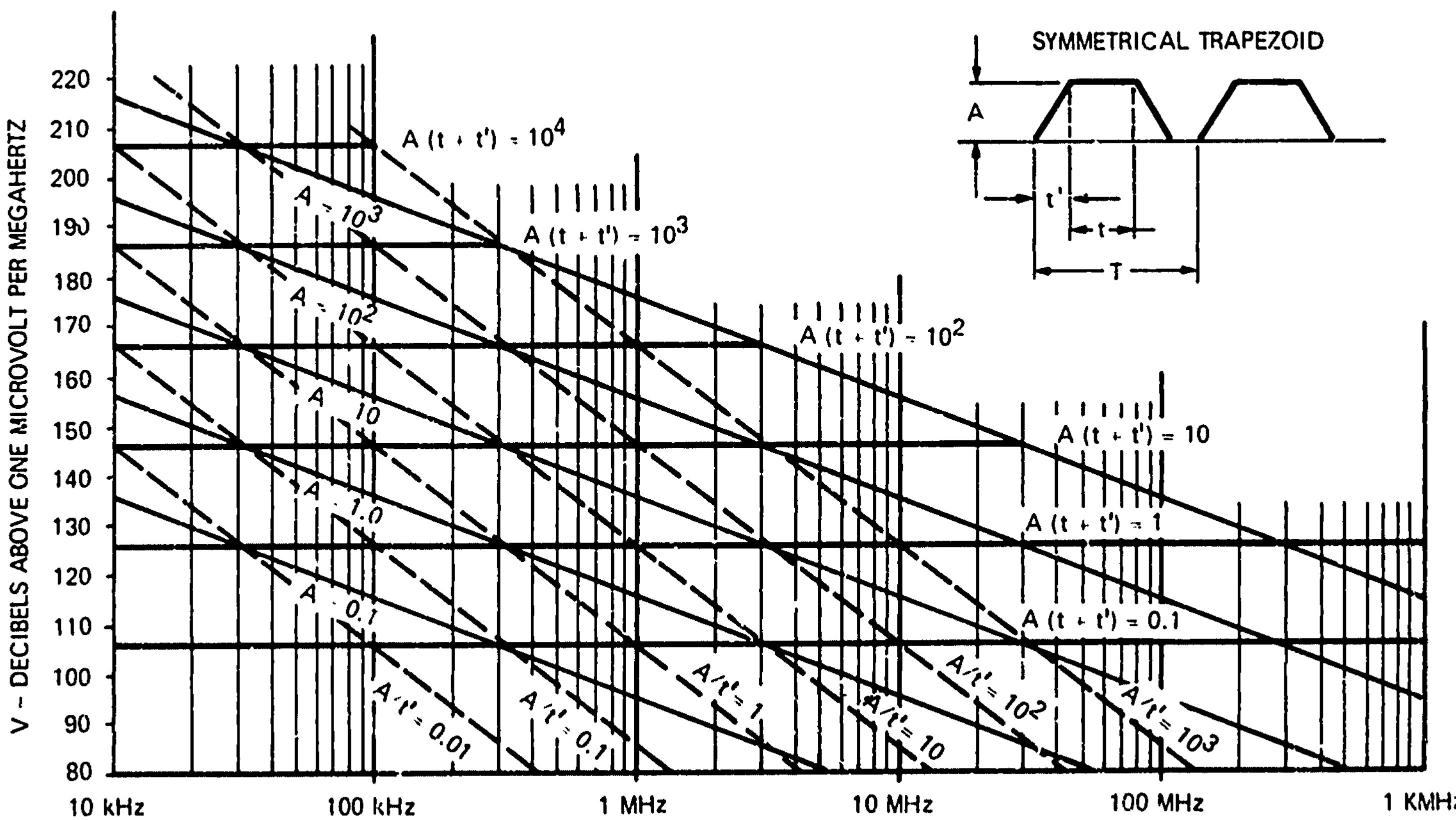


FIGURE 10-18 CONDUCTED INTERFERENCE FROM SYMMETRICAL TRAPEZOID

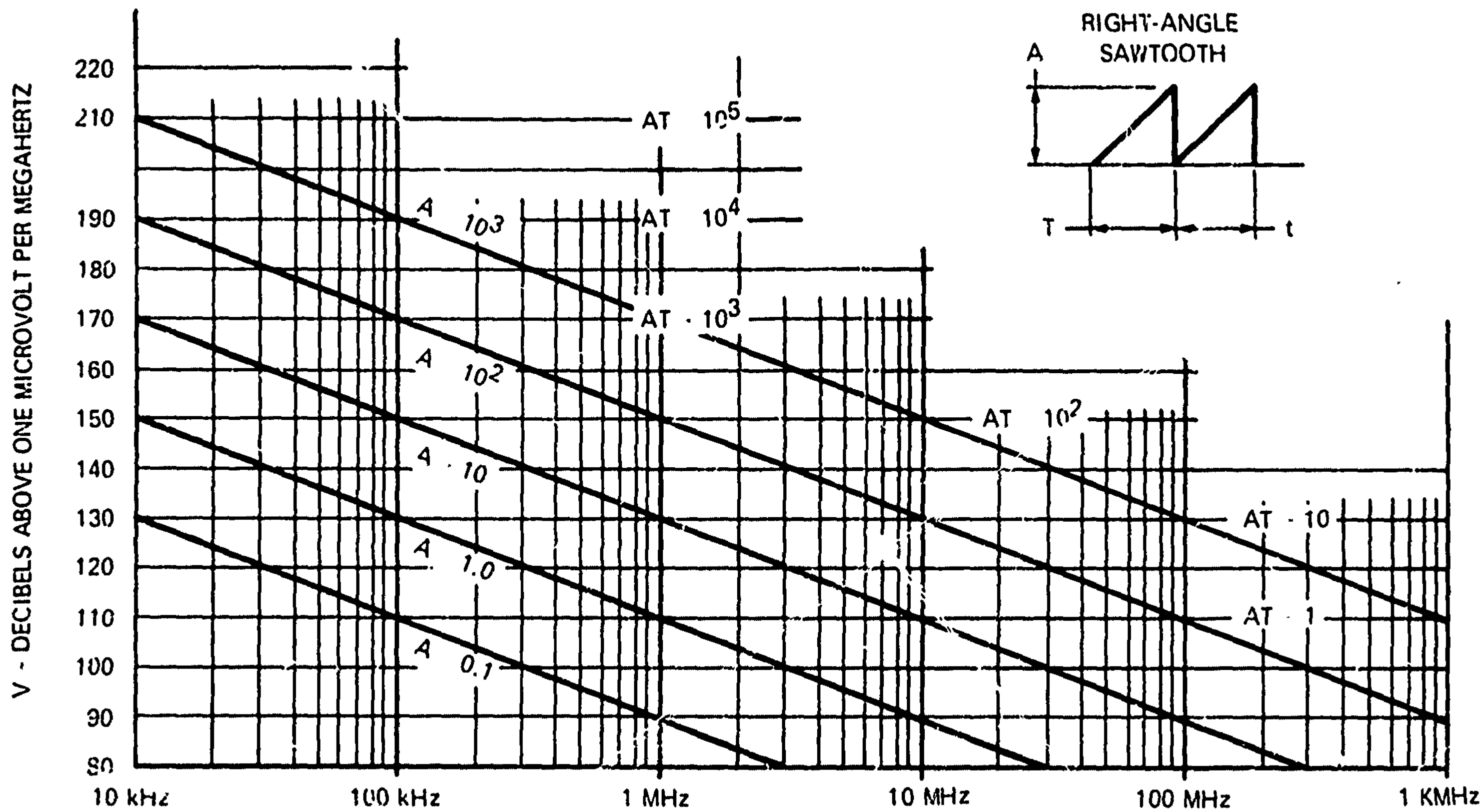


FIGURE 10-19 CONDUCTED INTERFERENCE FROM RIGHT-ANGLE SAWTOOTH

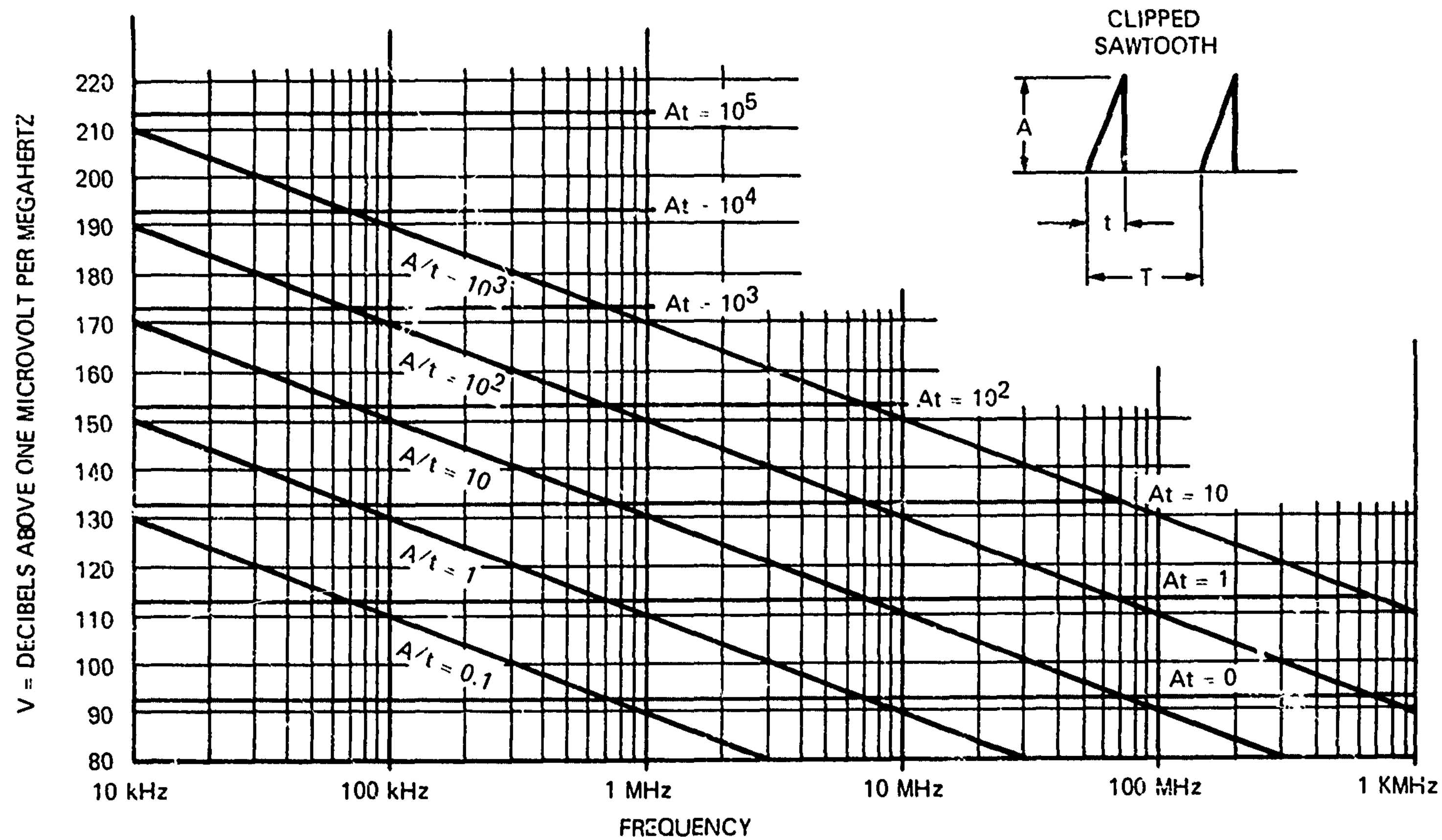


FIGURE 10-20 CONDUCTED INTERFERENCE FROM CLIPPED SAWTOOTH

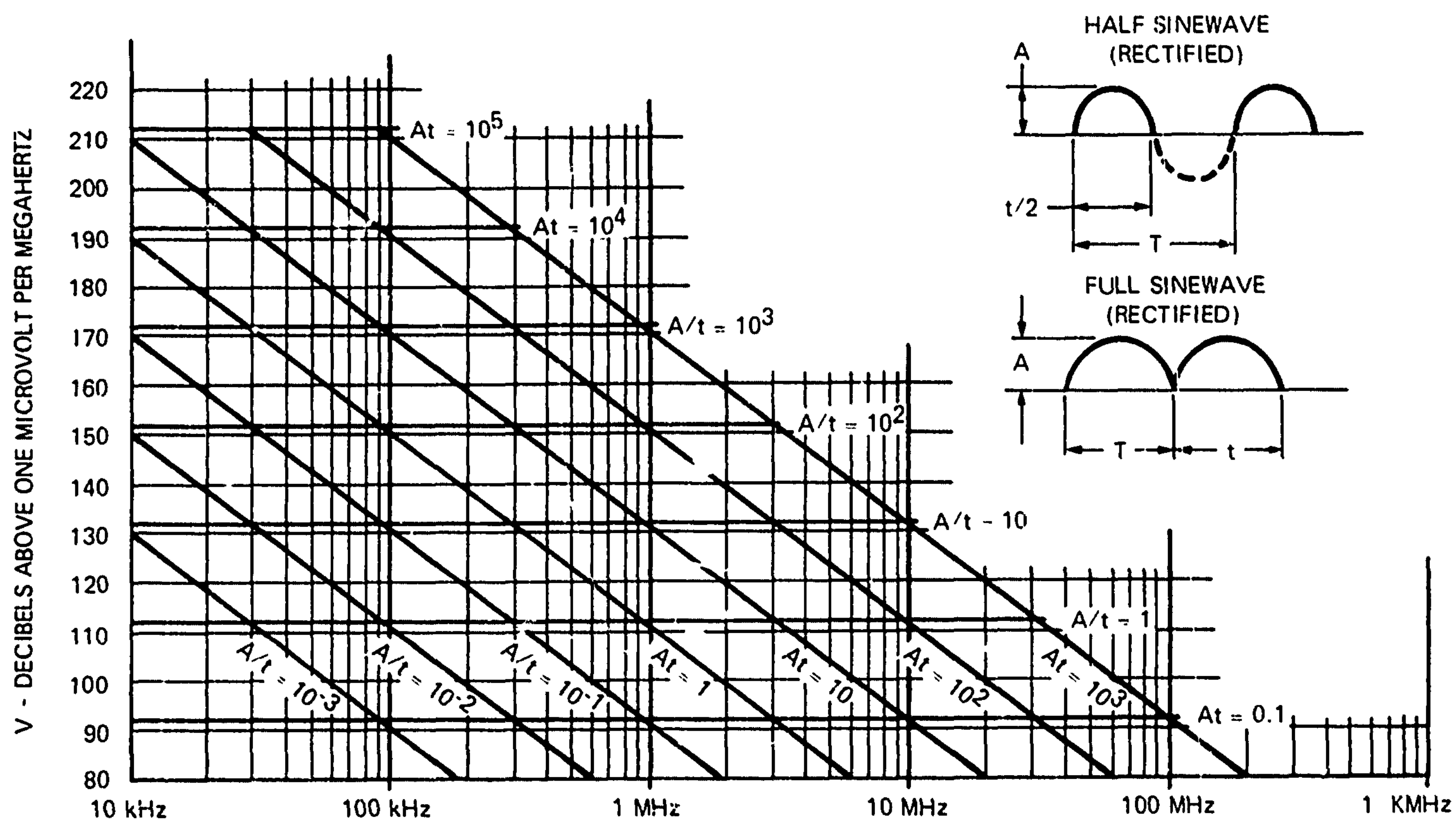


FIGURE 10-21 CONDUCTED INTERFERENCE FROM RECTIFIED SINEWAVE (CHART VALUES ARE FOR FULL SINEWAVE - SUBTRACT 6 DB FOR HALF SINEWAVE).

Prediction of Interference From Waveforms

Figures 10-15 through 10-21 are charts of typical spectral density amplitude envelope expressions, which are very convenient for predicting the conducted interference from any of the waveforms given in Figure 10-14 or from other waveforms that are combinations of these waveforms. The vertical scale is a linear one that expresses the maximum peak reading of an interference meter in decibels above one microvolt per MHz as obtained by substitution with a calibrated impulse generator. The horizontal scale is a logarithmic scale of frequency in megahertz.

The horizontal and downward-sloping lines drawn on the chart are plots of the expressions for the various frequency functions associated with each waveform. The horizontal lines in all cases are associated with values of pulse area; that is, the total energy content of a single pulse. The sloping lines are a family of curves that expresses either a function of rise time or an appropriate amplitude for the function under consideration. To use the charts, the values of the pulse area, the rise time of the pulse (if other than instantaneous) or some function of rise time, as indicated, must be calculated.

The charts are used to generate a complete curve of peak broadband conducted interference amplitude versus frequency for any given pulse waveform. To generate this curve, enter the chart on a horizontal line corresponding to the pulse area, At. Follow this line until it intersects the least-sloping line corresponding to the calculated amplitude or rise-time function, as appropriate. Follow this sloping line until it intersects either the horizontal axis or a more steeply sloping line corresponding to a second function of rise time or amplitude. An alternate method of forming the curve is to reverse this procedure. Start at the highest frequency of concern and enter the steepest sloping line, follow it until it intersects a less steeply sloping line, and so until the vertical axis is reached.

To illustrate the use of the chart, an example is given on the calculation of the frequency spectrum of the conducted interference generated by a square wave. Assume the following conditions:

A = 10 volts

t = 1 microsecond

repetition frequency 1/T = 50 kHz

1. Calculate At

   At = 10 × 1 = 10 volt-microseconds
2. Enter the chart of Figure 10-15 from the left on the horizontal line marked At = 10. Follow this line right to the point where it intersects with the downward-sloping line marked A = 10. Now follow this downward-sloping line until it intersects with the horizontal axis.
3. The curve that was traced may be transferred to a graph sheet directly, or it may be marked and read off directly from Figure 10-15.

The values on the plotted curve are 146 decibels above one micro-volt per megahertz at any frequency from 50 kilohertz (the fundamental frequency) to a frequency of 320 kilohertz. From this point, the maximum value of interference

falls at a constant rate of 20 dB per decade, or 6 dB per octave, following the line A = 10.

In the example, the curve drawn is discontinuous at a frequency of 50 kHz because this frequency is the fundamental frequency of the assumed square wave. This means that there is theoretically no response at lower frequencies. This downward-sloping curve for A = 10 intersects with the horizontal line At = 10 at a value of 146 dB above one microvolt per MHz and a frequency of 320 kHz. The frequency at this intersection of lines, where there is a slope change, is called a "corner frequency." The downward-sloping curve has no theoretical upper frequency limit; therefore, it can be extended indefinitely, and it decreases at a rate of 20 dB per decade, or 6 dB per octave. To find the value of interference at 1000 MHz presuming no curvature at waveform corners, simply extend the vertical scale to sufficiently lower values and extend the straight-line curve. It also may be calculated very simply from the known dB-per-decade slope and the known interference level at some point shown on the graph. The interference level shown on the curve for A = 10 at 100 MHz is 96 dB above one microvolt per MHz bandwidth. The interference level at 1000 MHz, which is one decade higher in frequency, is 20 dB lower than the level at 100 MHz; thus, the interference at 1000 MHz if

v = 96 - 20

v = 76 dB above 1 microvolt per megahertz

The peak harmonic amplitude of a symmetrical trapezoid pulse always has two corner frequencies; that is, two changes of slope. The prediction chart for conducted interference from a symmetrical trapezoid is given in Figure 10-18. This chart and the others are used in exactly the same way as the example given above. The following example illustrates the use of the chart for a symmetrical trapezoid or for any other waveform that has more than one corner frequency. Assume a symmetrical trapezoid with the following characteristics:

Repetition frequency = 222.2 kHz

$T = 1/222.2$ kHz = 4.5 microseconds

t = 50 nanoseconds - 0.050 microseconds

t' = 100 nanoseconds = 0.100 microseconds

A = 8 volts

1. Calculate $A(t + t') = 8(0.05 + 0.1) = 1.2$ microsecond-volts
2. Calculate $A/t' = 8/0.1 = 80$ volts per microsecond
3. Enter the chart of Figure 10-18 near the horizontal line marked $A(t + t') = 1$. The exact location of the horizontal line above $A(t + t') = 1$ may be found by converting the ratio 1.2/1 into decibels $20 \log_{10} 1.2 = 1.6$ dB; thus, the correct horizontal line is at 126 pulse 1.6 dB above one microvolt per megahertz. The error will not be appreciable if the chart is entered directly on the horizontal line corresponding to $A(t + t') = 1$.
4. Follow the horizontal line to its intersection with the solid sloping line marked A = 10. This value is too large because A is 8 volts for the problem. The exact location of the sloping line may be found by converting the ratio 10/8 into decibels as $20 \log_{10} 10/8 = 2.0$ dB,

which indicates that the sloping line for 8 volts is 2 dB below the line marked A = 10. To read the value at any selected frequency; take the intersection of the A = 10 line with the frequency ordinate and drop down 2 dB. This is the value for A = 8 volts. The intersection of the line for A(t + t') = 1.2 when the A = 8 line is at about 2.2 MHz.

5. Draw in a line for A = 8 two dB below the A = 10. Also draw in a line for A/t' = 80, which will be 2 dB below the A/t' = 10^2 broken line. These two lines will intersect at about 3 MHz.

6. Follow the new line for A/t' = 80 downward until it intersects the horizontal axis at about 40 MHz.

The path traced along the horizontal line and the two sloping lines completely describes the maximum-amplitude envelope for broadband conducted interference from the trapezoid. The two corner frequencies are at the intersections of lines in which changes occur. The interference level will be constant at approximately 127.6 dB above 1 microvolt per MHz from 222.2 kHz to the first corner frequency (2.2 MHz). It will then decrease with frequency at a rate of 20 dB per decade (6 dB per octave) until the next corner frequency is reached. This second corner frequency is at approximately 3 MHz. From this frequency, the interference will decline at the faster rate of 40 dB per decade (12 dB per octave) to any higher frequency. Theoretically, there will be no interference at any frequency below 222.2 kHz, because this is the fundamental frequency. The interference at frequencies above 40 MHz will continue to decline at the rate of 40 dB per decade.

The interference at higher frequencies, where the lines run off the graph, can be calculated very simply by using the known value from the broken line corresponding to A/t' = 80 at any arbitrary frequency and by subtracting 40 dB for each decade of frequency increase. For example, the value of interference of 104 dB above 1 microvolt per MHz at 10 MHz can be used to calculate the interference level expected at 1000 MHz. Since 1000 MHz is two decades above 10 MHz, the interference level will be 40 × 2 = 80 dB lower than at 10 MHz, or 104 – 80 = 24 dB above 1 microvolt per MHz. This corresponds to a reading of 16 microvolts per MHz of bandwidth.

For an analysis of specific pulse waveforms identical or similar to those shown in Figure 10-4 but not within the range of the charts given in Figure 10-15 through 10-21, charts may be constructed either from the equations given on the right side of Figure 10-14 or by extending the scales on the appropriate chart and by adding horizontal and sloping straight lines that parallel those now shown on the charts.

If the response must be predicted in terms of current rather than voltage, the waveform may be plotted in terms of amperes versus time rather than volts versus time. Once the waveform has been expressed in terms of amperes, the charts may be used directly as drawn, but the units of the vertical axis become decibels above one microampere per megahertz; the numerical values remain unchanged.

Radar Systems

Radar systems used in aircraft use several modulation techniques. Chief in importance among these are unmodulated CW (doppler) radar, pulse radar, and frequency sweeping (chirp) radar. The first consists of a carrier and no modulation, while the latter two are essentially specialized AM and FM modulation techniques.

The spectrum of unmodulated CW radar is quite simple; it consists only of an unmodulated carrier and harmonics of this frequency. Unmodulated CW radar, however, accounts for only a small minority of radar systems, since only velocity information can be deduced from the return echo. Its major use in aircraft systems is in a system that computes the actual ground track of an aircraft.

Most radars are either of the pulse or chirp type, since these techniques provide a method of target ranging.

Pulse radar uses a form of amplitude modulation, and the spectrum can be computed by Fourier Analysis of the modulating pulse. The emission spectra can be quite wide, depending on the type of pulse used as a modulating waveform.

The simplest form of modulating waveform is the rectangular pulse. This waveform, since its risetime is rapid, results in a worse case spectrum. An example of the spectrum of a rectangular pulse is repeated in Figure 10-22. It is seen that the slope of the envelope of the interference levels is 20 dB per decade.

If a trapezoidal pulse is used, the interference at higher frequencies (large difference frequency between carrier and sideband) is greatly reduced because the slope of the envelope beyond a certain point becomes 40 dB/decade.

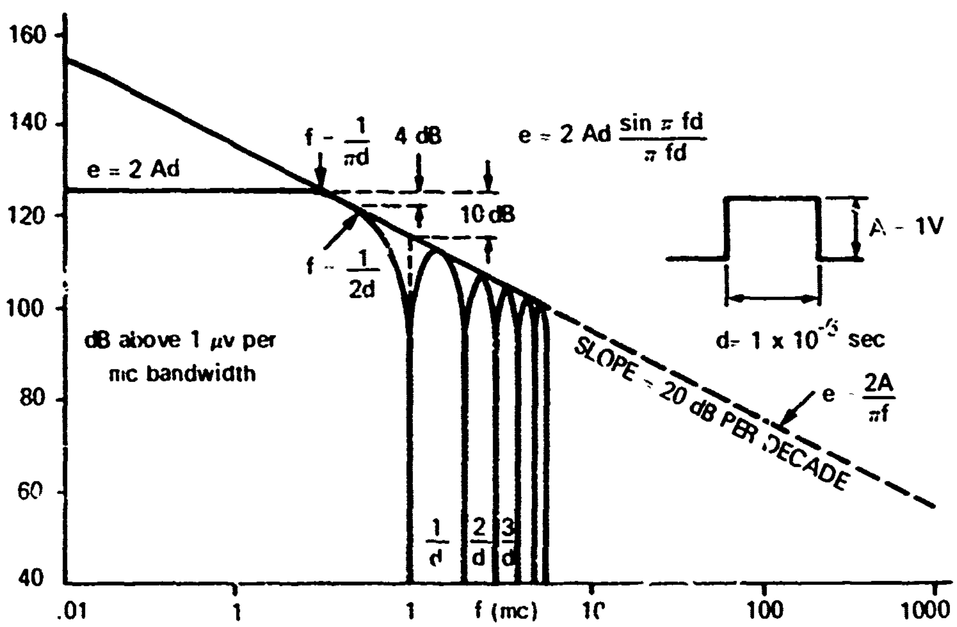


FIGURE 10-22 INTERFERENCE LEVEL FOR A 1 VOLT, 1 SEC RECTANGULAR PULSE

Figure 10-23 illustrates a similar straight line approximation for a trapezoidal pulse. Inspection of the graph reveals that the spectrum envelope consists of three portions, a level portion, a 20 dB per decade slope, and finally, a 40 dB/decade slope that continues indefinitely. Included in the figure are the defining equations for each portion of the envelope, as well as the expressions for the two corner frequencies. The first corner frequency depends primarily on the duration of the pulse, while the second primarily depends on the rise time of the pulse.

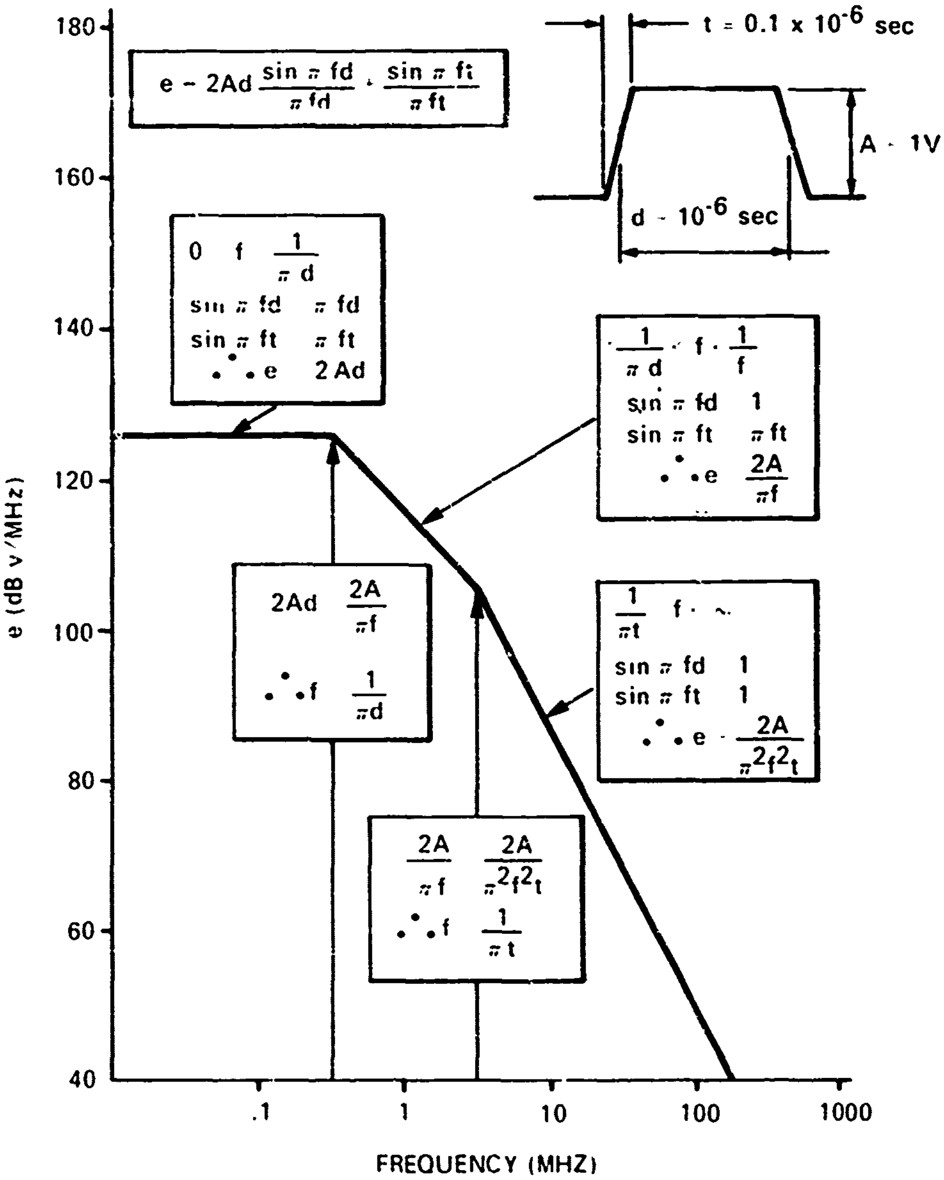


FIGURE 10-23 INTERFERENCE LEVEL FOR A 1 VOLT, 1 SEC TRAPEZOIDAL PULSE

Figure 10-24 illustrates the spectrum envelope for various combinations of pulse duration and rise times.

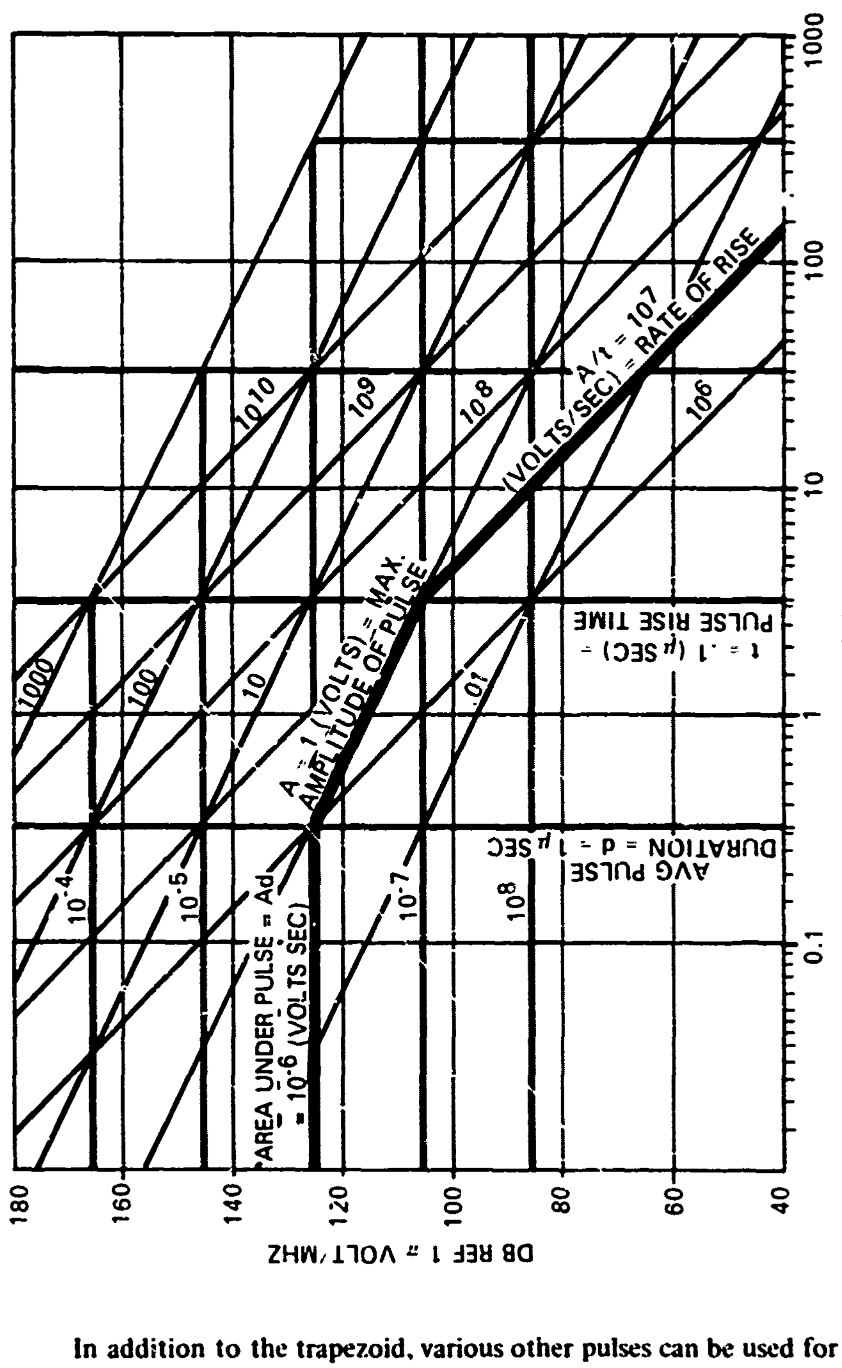


FIGURE 10-24 INTERFERENCE FROM A TRAPEZOIDAL PULSE FOR VARIOUS AMPLITUDES AND RISE TIMES

In addition to the trapezoid, various other pulses can be used for radar purposes. These include triangular, sawtooth, exponential, gaussian and cosine, etc. Figure 10-25 illustrates the spectrum envelope for these other types of pulses.

It would appear from the above that the solution to pulse radar interference lies in merely choosing a waveform with a narrow frequency spectrum. This unfortunately reduces the resolution of the radar. Therefore, any solution must be a compromise between resolution and bandwidth.

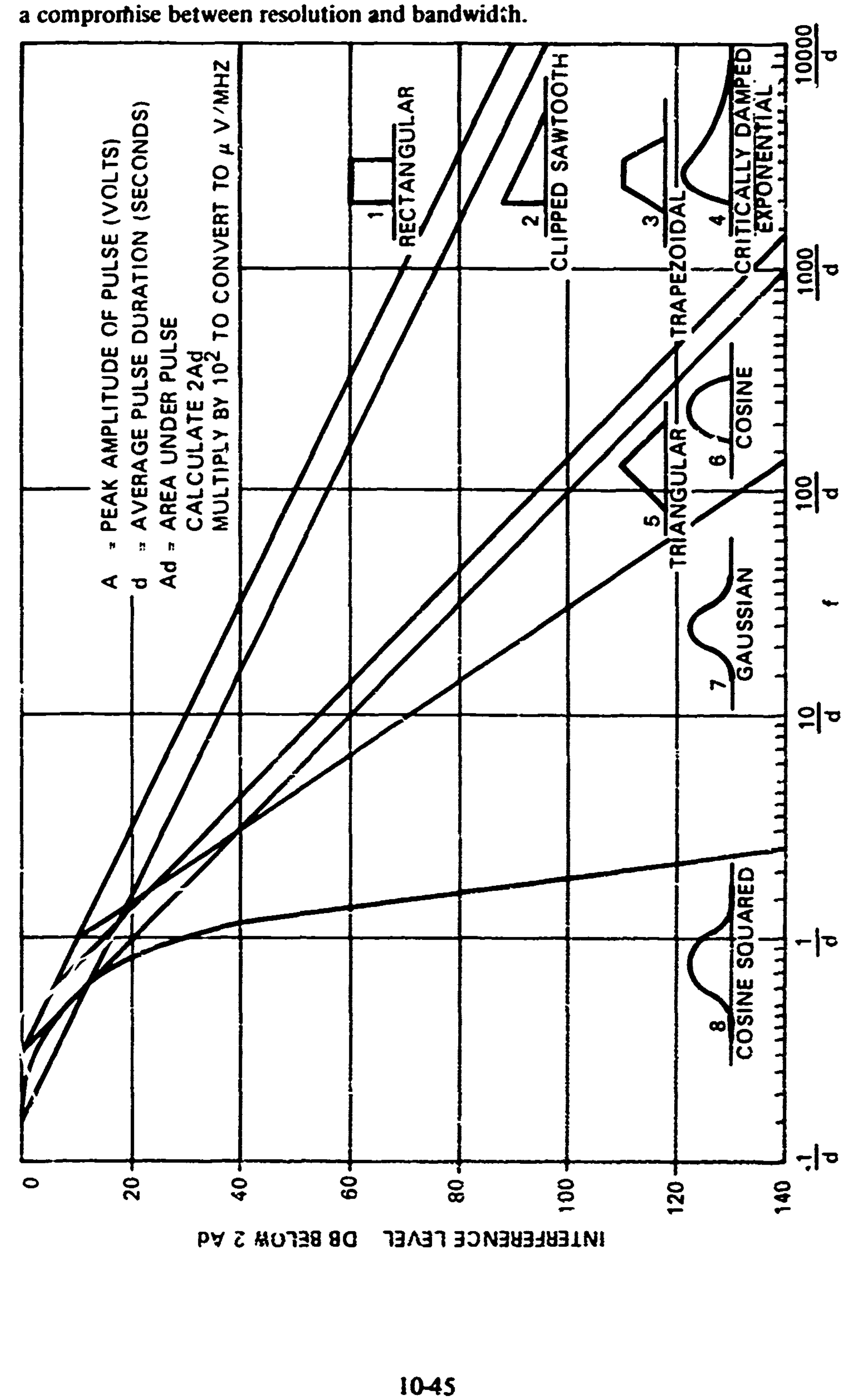


FIGURE 10-25 INTERFERENCE LEVEL FOR VARIOUS PULSE SHAPES

There are some forms of pulses, however, which have better resolution properties than others. The resolution effectiveness is rated in terms of the autocorrelation function of the pulse. It is important that the autocorrelation function have a single relatively narrow peak, since this peak is used to determine timing. It is, furthermore, important that other lesser peaks in the function be small with respect to the main peak since other peaks can cause false returns and ambiguity. The realization of this fact has resulted in the development of complex pulse structure chosen to minimize ambiguity. An example of a radar employing such a technique is one using Barker Code modulation. A Barker Code is a set of digital states with an autocorrelation function that has a single peak with all lesser peaks at a small uniformly low level. A pulsed radar using such a code would transmit a series of bursts, each of which was amplitude-modulated by a digital waveform comprised of the Barker Code. The EMC analysis of such bursts would be completed by considering the burst to consist of the sum of a number of rectangular and triangular pulses.

FM radars are used for such purposes as moving target indicators and radio altimeters. In most systems, a relatively simple sweeping waveform is used for the modulation. The spectrum resulting from this type of modulation is generally strongest near points where the deviated carrier remains longest. Examples of several FM spectra are given in the section "Complex Waveform Analysis." Detailed analysis of complex frequency modulation is difficult because the modulated signal must be analyzed. In general, if the modulating index is high, significant modulation components are concentrated in a bandwidth only slightly greater than the total frequency deviation.

Use of Statistical Data for NAVAIR Nomenclatures

Most Federal nomenclature (AN/- - -) transmitting and receiving equipments have been subjected to EMC testing resulting in a measurement of typical emission spectra. Data have been taken on a sufficiently large number of equipments of a particular nomenclature to develop an indication of the variance in amplitude and frequency of emissions applicable to all equipments in the particular nomenclature. The resulting measured data is expressed as a plot of the amplitude of emission components versus frequency for the nomenclature. An example of this type of graph is illustrated in Figure 10-26.

If this data are available for various AN/equipments that are candidates for use in a NAVAIR System, the data can be used for a paper study of the degree of intrasystem electromagnetic compatibility. For instance, if it is determined that a certain transmitter is likely to have a spurious level at some particular frequency, either a different transmitter must be used or the system receiving frequencies must be selected to avoid the frequency of the spurious emission. Similarly, data on the receivers must be analyzed to determine if the receiver has a spurious response on the same frequency as the transmitter spurious emission.

INCIDENTAL SOURCES

Incidental sources include all systems on the aircraft that generate spurious

emissions incidental to their function. An example of any incidental source is an electric motor. The sparking in the commutator produces an emission, at radio frequencies, but these RF signals do not have any function in the motor.

As the name implies, one of the chief attributes of incidental emissions is that they are not predictable. Rather, the principal method of achieving EMC where the source is incidental is to recognize the possibility of interference and use adequate shielding, filtering, grounding, and bonding, both on the victim and source device.

General Classes of Incidental Emissions and Spectra

Incidental emissions can be classed roughly as impulsive pulsatile, random, periodic, or nonperiodic, depending on their general character when expressed in the time domain.

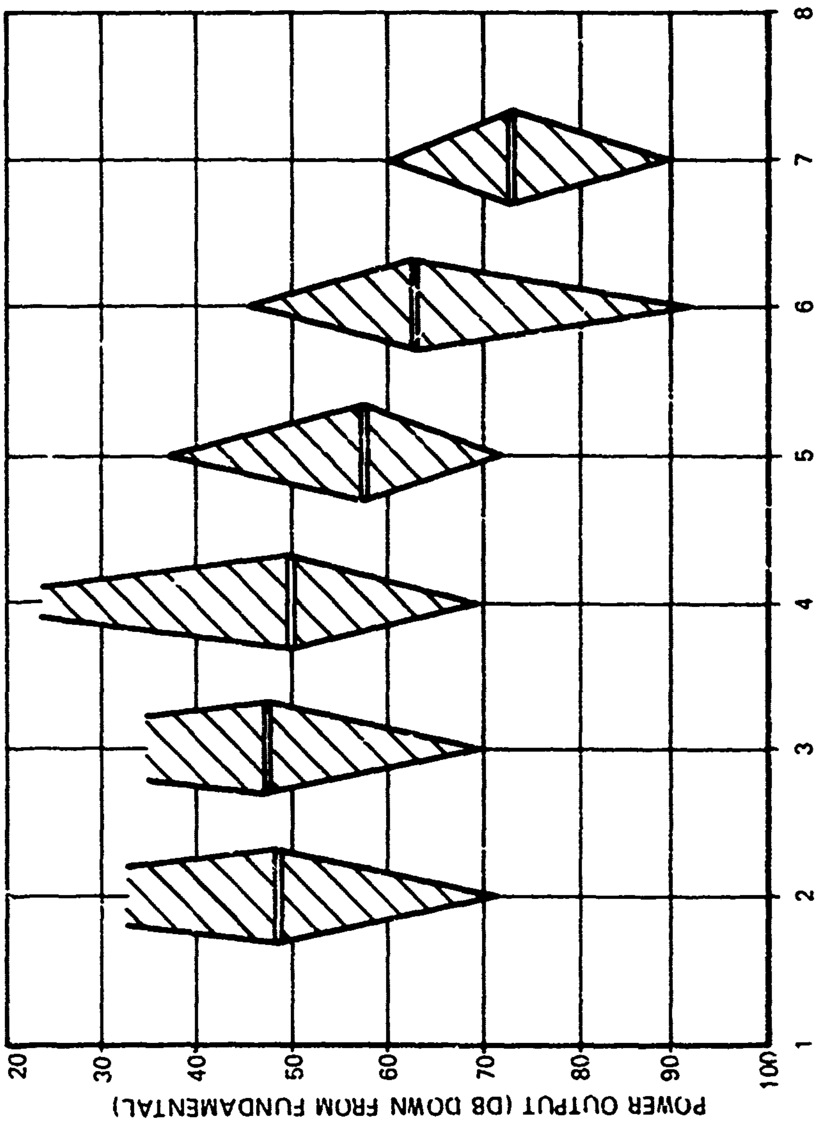


FIGURE 10-26 RANGE OF 33 MEASUREMENTS AT EACH HARMONIC FOR THE SAME TRANSMITTER NOMENCLATURE

EMI impulses are generated in discrete energy bursts that have a characteristic wave shape of their own. The impulse may be a single occurrence, such as that resulting from a single operation of an electrical switch or relay, or it may be a series of regular occurrences such as the signal from an automobile ignition system. Impulse signals may be considered to consist of non-overlapping transients. The spectrum of a given impulse or series of impulses may be calculated by using the conventional Fourier Analysis.

Pulse signals are commonly used in digital systems. The simplest form of a pulse signal is a square wave. The waveforms used in most systems are, however, more complex and involve modulation of the otherwise regular pulse signal. This modulation can consist of coding the pulse states and modulating the amplitude, width, frequency, or phase of the pulse stream. Like impulse signals, the spectrum of pulse trains can be computed by Fourier Analysis.

Random signals vary in a completely irregular manner with time, and are therefore unpredictable at any given instant. Some typical sources of random EMI are gas discharge tubes, thermal noise, and atmospheric noise. Random noise is similar to impulse noise except that the random noise impulses are no longer distinct but may overlap partially or completely.

In some situations, the response of the victim device or receiver may obscure the distinction between random and impulse signals. The same interference source may produce impulse noise in one system and random noise in another, depending upon the response time of the two systems. The need for distinguishing between the two types is important, since the specific method of EMI evaluation for a specific receiving device depends on the type of emission present. An example of the type of interference being affected by the reaction of the affected device would be in the signal from an ignition system. If the device affected by the initial impulse of the ignition system is not capable of recovering and returning to normal operation before the second impulse is received, a cumulative reaction from successive emissions will result.

The characteristics of a periodic signal include a cyclic or systematic amplitude or frequency variation as a function of time. At given times, certain variations repeat. This type of signal is produced by most communication and radar transmitters. Other devices such as rotating machinery and pulse timing devices can produce periodic types of signals or interference. Most forms of modulation used to transmit information can be considered periodic signals.

Aperiodic signals comprise disturbances that do not repeat in the time domain. Because of this, the spectrum of an aperiodic signal is continuous rather than being composed of discrete components. In aircraft systems, aperiodic signals are caused by one-time event, such as activating electrical switches. Aperiodic signals are often overlooked as a potential source of interference since their presence is infrequent. Aperiodic signals can be, however, a significant EMC hazard, particularly where the victim system timing is interfered with or some important functional signal is simulated. An example of the latter is the occurrence in a weapon system of a noise burst that simulates the electrical command to fire.

Description of Possible Incidental Interference Sources Germaine to Naval Air Weapon Systems

On-Board Avionics Computers

Digital computers are used for several purposes in NAVAIR systems including processing of radar data and operation of weapon systems. Modern computers produce digital signals at high data rates. In sophisticated high speed machines the base frequency of the data may be in the HF or even VHF portion of the spectrum. Even slower systems often use waveforms having nanosecond range rise times. These signals can cause serious emissions over broad portions of the RF spectrum unless there is proper shielding and grounding. The compatibility problem worsens with increasing speed of the machine due to the fact that higher speed digital logic also employs higher current, making more RF energy available.

Aircraft Flight Controls

Aircraft flight controls use everything from digital signals similar to those used in computers to servo motor positioning devices. Noise generation from the former is similar to that from computers. The latter may contribute broadband type noise resulting from contact arcing. Furthermore, if current levels are high, there may be some difficulty with magnetic proximity effects.

Weapon System Controls

Weapon system controls are, in terms of electrical signaling procedures, quite similar to flight controls, and include motors, switches, digital signals, and analog voltages. The incidental emissions from such systems are therefore of the same form as those associated with flight controls.

Others

Any electrical or magnetic equipment on board the aircraft can cause incidental interference. Thus, any motor, switch, indicator, or even electric light could be a source of interference. The EMC systems designer must consider all possible sources of interference. Often the mechanism responsible for the interference is obscure and the probability of interference small, but sometimes even a single incidence of interference can be hazardous in flight.

Possible sources of interference are not confined to active electromagnetic devices. Passive elements can act to create spurious emissions. Of particular importance in this regard are poor metallic joints in the aircraft. Such a joint can act as a spurious diode and cause spurious components derived from transmitter emissions to occur at sum and difference frequencies. This effect can jam otherwise clear communications channels in the aircraft receivers.

INTERFERENCE COUPLING PATHS AND MECHANISMS

GENERAL

The environment of the naval aircraft is fraught with potential EMI hazards. The electromagnetic interference in this type of system derives from equip-

ment placement and limited space available for antenna separation. NAVAIR operations require that a variety of radar, communications, EMC, and flight control systems and subsystems be in simultaneous use. The proximity of wiring, equipment, and antenna affords abundant opportunities for unintentional coupling. Moreover, the aircraft platform places severe weight restriction upon the equipment. This often necessitates that less shielding and filtering can be used than would otherwise be considered the normal precaution in a ground base installation of similar complexity. An additional difficulty in aircraft lies in the grounding system. Since the aircraft is an isolated entity, the ultimate ground mode is the structure of the aircraft itself. The interaction between portions of this structure and various other conductors in the grounding system can lead to forms of coupling that are often obscure in origin.

Paths and mechanisms for coupling electrical energy from a source to a receptor may be due to conduction or radiation or both. The conduction mode implies a direct "hard" connection such as through a power line or signal line, whether it is wire or wave guide. The radiation mode implies that no "hard" connection is responsible for coupling energy from a source into a receptor. Other forms of coupling that require no connection include induction coupling as well as capacitive coupling. These are, in fact, due to near field electromagnetic effects. In the far field, coupling is by means of the radiation field. Each of these methods will be discussed.

INDUCTIVE COUPLING

Inductive coupling is one of the near field effects by which EMI may be transmitted from a source to a receiver. The basic coupling mechanism is predominantly a linking of magnetic flux between two circuits. It is particularly significant where relatively high currents are involved. However, it should be pointed out that large powers are not required to produce large current. Low impedance circuits will foster large currents with low voltages. A bypass or filter capacitor, for example, at series resonance with the wiring inductance may still have an appreciable Q. Thus the wiring of this capacitor inside the equipment may constitute an excellent loop to couple interference to and from other portions of the circuitry.

Calculation of mutual inductance between loop elements is a complex function of loop geometry and current distribution in the loops. Mutual inductance between coaxially mounted loops separated by distance d, if the ratio of loop diameters is large, is given by the expression:

$$M_{21} = \frac{\mu \pi a^2 b^2}{2(d^2 + a^2)^{3/2}} \qquad (10\text{-}6)$$

where:

a = radius of large loop

b = radius of small loop

μ = permeability

for

$a = 3$ inches

$b = 0.3$ inch

$d = 6$ inches

$M_{21} = 43$ picohenries

The induced voltage in the second loop due to a current $I_1 = I_0 \sin(\omega t)$ is given by

$$V_{21} = M_{21} \omega I_0 \cos(\omega t) \qquad (10\text{-}7)$$

At one megahertz, one ampere of current in loop 1 would produce an induced voltage of 43 microvolts in loop 2.

Another example of inductive coupling is that existing between two parallel unshielded wires, where the return paths are through the grounding system. Mutual coupling between such loops is again a function of loop geometry. In general, however, it is related to the product of the areas of the loops, which may be quite large.

Shielding of magnetic fields, particularly at low frequencies, is a critical design area. At very low frequencies, below 1000 Hz, the effectiveness of nonpermeable metals in reasonable thickness is quite limited. The shielding effectiveness may also be greatly reduced by discontinuities in the shield such as poor radio-frequency contact at enclosure seams, holes, corrosion, and general physical degradation through use.

CAPACITIVE COUPLING

When the source is high impedance, the near region of the field is predominantly electric and the coupling mechanism between two circuits is capacitive.

Capacitance between two number 10 wires running parallel at a separation of twelve inches is approximately seven picofarads per meter of length. At one-quarter inch separation in air, capacitance increases to about 18 picofarads/meter. At 50 kHz two ten-foot lengths of such wire would have a capacitive reactance between them of only 60,000 ohms. This would represent a voltage attenuation (insertion loss) of 60 dB to a load impedance of 60 ohms. Obviously for higher frequencies and higher load impedances, attenuation would be even less.

Using the earlier example of a 100 Hz rectangular wave, the harmonic voltage content at 50 kHz is approximately 33 dB below that of the peak-to-peak voltage variation. Thus for a one volt peak-to-peak variation at 100 Hz, this wir-

ing would couple a voltage of -93 dBV into the adjacent circuit at 50 kHz. This is 27 dB above one microvolt, or 22 microvolts.

Capacitive coupling also exists between equipments. Unless adequate high-frequency grounding of equipment enclosures is provided, interference voltages may be large enough to cause serious capacitive coupling problems.

RADIATION COUPLING

The term "radiated interference" is commonly used to describe any interfering signal transferred through a medium by an electromagnetic field. This includes the radiation field as well as the coupling through mutual inductance and capacitance. Strictly speaking, the radiation field represents the energy that actually escapes from a source and propagates through space according to the laws of wave propagation.

When an electrical current flows, an electromagnetic field is set up. When the current is interrupted, most of the energy in the electromagnetic field returns to the conductor. The process is continuous in the case of an alternating current. Most of the energy returns to the conductor, but a part of it never returns and is propagated out into space. This constitutes the radiation field.

The electromagnetic field about the conductor can be described in terms of an electric, E, field and a magnetic, H, field mutually perpendicular. If the current source has a low impedance, the current will be large in proportion to voltage and the field will have a large H component in respect to the E component. This will be described as a low impedance or magnetic field, and the coupling mechanism will be termed "inductive coupling." However, if the current source is high impedance, the current will be small in relation to the voltage and the field will have a large E component in respect to the H component. This will be described as a "high impedance" or "electric field," and the coupling mechanism will be termed "capacitive coupling." The low impedance or high impedance fields exist within a short distance of the source. As this distance (in terms of wavelength) becomes large, the field assumes a characteristic impedance of the propagation medium. The impedance of space is approximately 377 ohms.

The magnitude of the E and H components of the field is related inversely to the distance, r, from the source. Very close to the source, magnitude will vary as $1/r^3$ and $1/r^2$, while at some distance the magnitude follows a $1/r$ relationship. The region where the $1/r$ component is large is called the "far field" while the "near field" indicates the region where the higher order r or induction terms dominate. At a distance of about one sixth of a wavelength, the $1/r$ or radiation field is equal to the $1/r^3 + 1/r^2$ or induction field. Beyond $\lambda/6$ the radiation field predominates.

Figure 10-27 shows the terminology generally accepted in describing the field regions. The transition between regions is a gradual one, and the actual transition point depends upon the error one can accept from the various functions. To obtain an expression for the transition between near and far fields, one assumes the antenna is large compared to the wavelength ($D >> \lambda$) and limits the space phase error to $\lambda/16$. This gives an expression for the distance, r, to the far field region of:

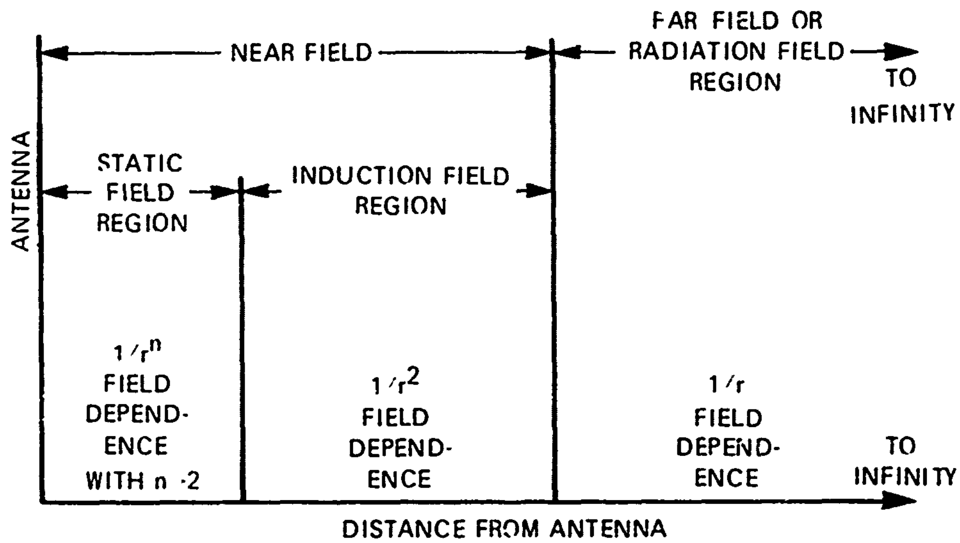


FIGURE 10-27 FIELD DIVISION DEPENDENCE ON DISTANCE FROM ANTENNA

When the antenna is not much larger than wavelength, the following criterion is adopted:

$$r \geqslant \frac{2D^2}{\lambda} \tag{10-8}$$

where:

r = transition distance measured along a normal axis from the antenna

D = maximum dimension of antenna

λ = wavelength at the operating frequency

$$r \geqslant 3\lambda \tag{10-9}$$

Actually both criteria must be satisfied for the far field.

When the interference signal is radiated through the electromagnetic environment, transmission losses are dependent on frequency, separation distance, terrain over which the signal propagates, electromagnetic properties of the medium, and other variables. In most interference analyses, one of the fundamental concepts of propagation loss is the free-space loss. The basic equation for free-space transmission loss for far-field conditions is:

$$L = 20 (\log_{10} f + \log_{10} d) + 37 \tag{10-10}$$

where:

L = free-space transmission loss in dB for line-of-sight transmission

f = frequency in MHz

d = distance in miles between the potentially interfering transmitter and the victim receiver

This equation assumes isotropic antennas where the gain of both transmitting and receiving antenna are unity.

Gains of transmitting and receiving antennas should be added to determine the total system loss from interference generator to victim device. The gains used in the computation are those in the direction of the propagation path between the two antennas. The loss from the free-space loss equation is usually a lower value than that expected from a signal propagated in a real world. Thus the worst case prediction of interference can use this lower value of free-space propagation loss.

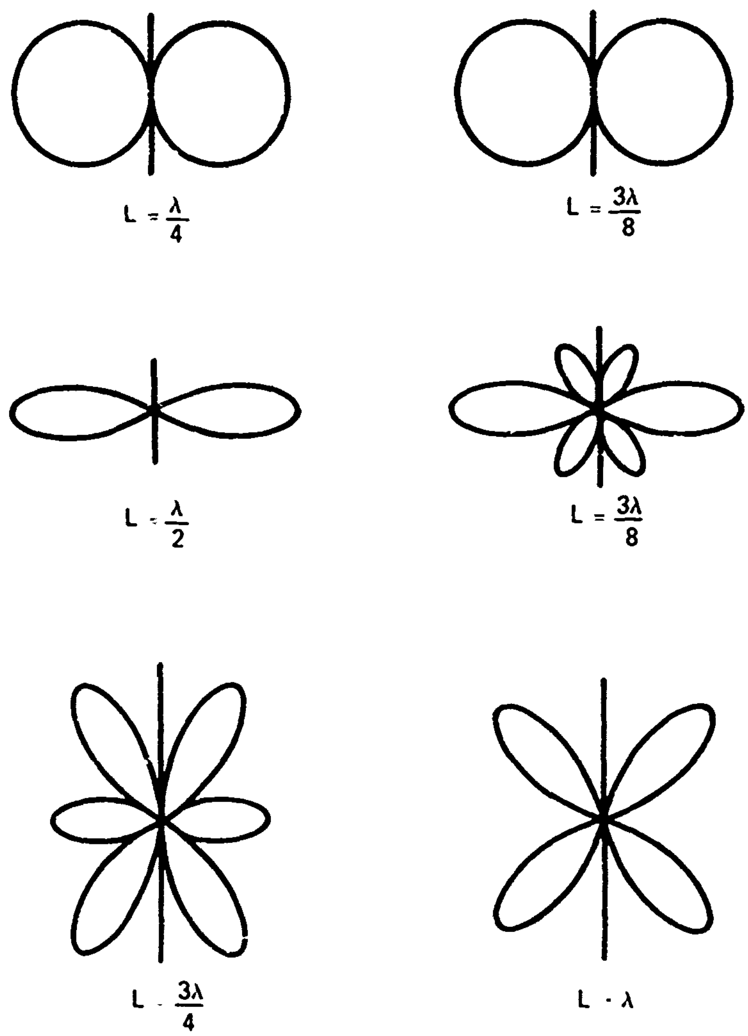
Other types of propagation should be considered when pertinent. Some of the types of propagation that may be important are:

1. Surface wave
2. Skywave
3. Ground reflected and multipath fields
4. Diffraction fields
5. Tropospheric and ionospheric scatter

In aircraft systems, coupling is sometimes caused by an analog of ground wave propagation. In ground wave propagation, the earth acts somewhat like a lossy one-sided waveguide causing propagation along the curved surface. In aircraft, the metal skin can act somewhat like the surface of the earth, and propagation can occur along the skin. This can cause coupling between antennas located on opposite sides, and even at opposite ends of the aircraft.

In the radiation field, the intensity of the electric or magnetic field is an inverse function of distance from the source. The field intensity at any point in a radiation field is also a function of the size and orientation of the radiator. For any body to be an efficient radiator, its electrical dimensions must be a significant part of a wavelength. Thus, although some sources have copious amounts of energy within the low frequency spectrum, little of it may be radiated because of short, ineffective antenna lengths. However, the extremely high sensitivities of modern receivers allow weak radiation fields to exhibit interference effects in the receiver. The radiation pattern is a useful way of comparing the spatial energy distribution of radiating bodies. Vectors are plotted radially from a point representing the source, with the length of each vector being proportional to the field strength at a fixed distance from the antenna in the direction indicated by the vector. A curve connecting the ends of these vectors has been called the radiation pattern.

Let us examine the radiation pattern of a dipole antenna of varying length while the frequency of the radiating source is held constant; or conversely, the length may be assumed to be constant while the frequency is varied. Figure 10-28 shows how the radiation pattern changes as the radiator varies in terms of wavelength. The problem of determining radiated interference at some point in space is complex because directivity of the antenna is an important consideration. Furthermore, the source radiator is not a well defined antenna structure and the interference signal may not be a sine wave.



WHERE L = LENTH OF THE ANTENNA
λ WAVELENGTH OF EXCITING SIGNAL

FIGURE 10-28 ANTENNA PATTERNS OF LINEAR RADIATORS

CONDUCTIVE COUPLING MODES

In the transmission of interference by conduction, the basic losses are the result of resistive and storage losses in the conducting material. Conduction losses are computed from electrical and physical properties of the conducting medium. For transmission along a cable path, the generated interference is confined to the physical dimension of the conductor, and the losses per unit length can be calculated from the conductivity and permeability of the conducting material. Losses for a waveguide can be similarly treated.

When a susceptible device is connected by common power supply wires to motors and generators, interference from the motors would be conducted to the instrumentation by the common power supply cables. This type of interference is usually reduced by filtering or impedance matching techniques.

There are several means by which conductive coupling is effective in addition to the simple means of conduction by a wire or cable outlined above. One such form of coupling is ground circuit conduction. In ground circuit coupling, both sides of the circuit, the signal wire and ground, support unintended conduction. The usual cause is that the circuit ground is resistively connected to the true ground, causing all portions of the circuit to be either AC or DC offset from ground. If an unintended signal is coupled into the circuit, most of the signal will be shunted to ground, but a small portion will be conducted by means of the defective local ground to remote points. Since other voltages in the circuit are established in part from the defective ground reference, the signal will appear on all of the circuit wiring when it is monitored with respect to true ground.

In balanced circuits, a similar phenomenon can be caused by minor imbalanced conditions anywhere along the circuit. This phenomenon is termed common-mode conduction. The typical symptom is that when equal signals measured with respect to ground are applied to each differential input line, a difference voltage appears at the output.

INTERFERENCE VICTIM DEVICES

GENERAL

Potential interference victims in naval aircraft might include any system involving electrical or electronic components. Particularly susceptible are equipments that involve low level signals and high gain amplifiers. Thus, the prime candidates for interference are communications, radar, ECM, and navigational receivers. Other systems that have high gain amplifiers include servomechanisms used in flight and weapons control.

The relative susceptibility of a system to electrical or electromagnetic interference is a complex function of many variables, including such phenomena as proximity to the culprit, degree of shielding, coupling isolation, and the design of the victim system. The systems having the best potential for interference-free operation are well shielded, well isolated, or avoid low level signaling and high

gain amplifiers. Since this latter consideration is often contrary to the purpose of the particular equipment, it is obvious that the design of an interference-free system is usually a compromise between what is generally construed to be good EMC design and important factors related to intended function of the equipment, its size, weight, and shape.

For purposes of analyzing their susceptibility, equipments and systems can be roughly categorized into functional and nonfunctional equipments. Functional victim equipment includes all communications, navigation, ECM, and radar receivers. As a category, these equipments are particularly susceptible to interference, since radio frequency energy is directly applied by means of an antenna, and operation is predicated on the amplification and processing of initially low level signals. The susceptibility of receiving equipments is principally a function of receiver design; and it is possible to a large degree to predict the deleterious effects of spurious responses due to mixer design, nonlinear amplification, etc. The susceptibility in receiving systems is primarily to the frequency selective or narrowband form.

Nonfunctional victim equipments include control systems, computers, displays, navigational aids, and all electrically actuated meters and displays. Interference in these systems stems from the unintentional coupling of high level RF signals. As a general rule, therefore, it is difficult to predict, from a prior knowledge of the equipment, that interference will occur, or from what source interference is likely. The solution to interference lies in proper shielding, grounding, bonding, and isolation from the source. The susceptibility of nonfunctional equipments is primarily to the broadband variety.

RECEIVING DEVICES

As stated earlier, receiving devices primarily exhibit a tunable or narrowband susceptibility characteristic. This results from the use of tuned stages throughout the receiver. Most frequency selective devices use filter networks that can attenuate frequencies outside the desired frequency range. In this case the interference frequency must be near the frequency of the network to produce an undesirable effect. The factors that determine how far from the design frequency the interference can exist before becoming negligible, are the strength of the interference relative to the desired signal and the Q of the filtering circuit at the desired design frequency. The Q of a circuit is a measure of how selective the particular circuit is relative to frequency, and is defined as:

$$Q = \frac{f_0}{(f_1 - f_2)} \qquad (10\text{-}11)$$

where

f_0 = the design (desired) frequency

$f_1 - f_2$ = the 3 dB bandwidth of the circuit

Typical selectivity of a circuit with a Q of 100 is shown in Figure 10-29. A higher Q would increase the sharpness of the curve and thus attenuate adjacent frequencies more effectively. If the strength of the interference is great enough to

compensate for the attenuation caused by the selective circuit and to produce an unwanted signal similar to the desired signal, interference and undesired effects can be produced.

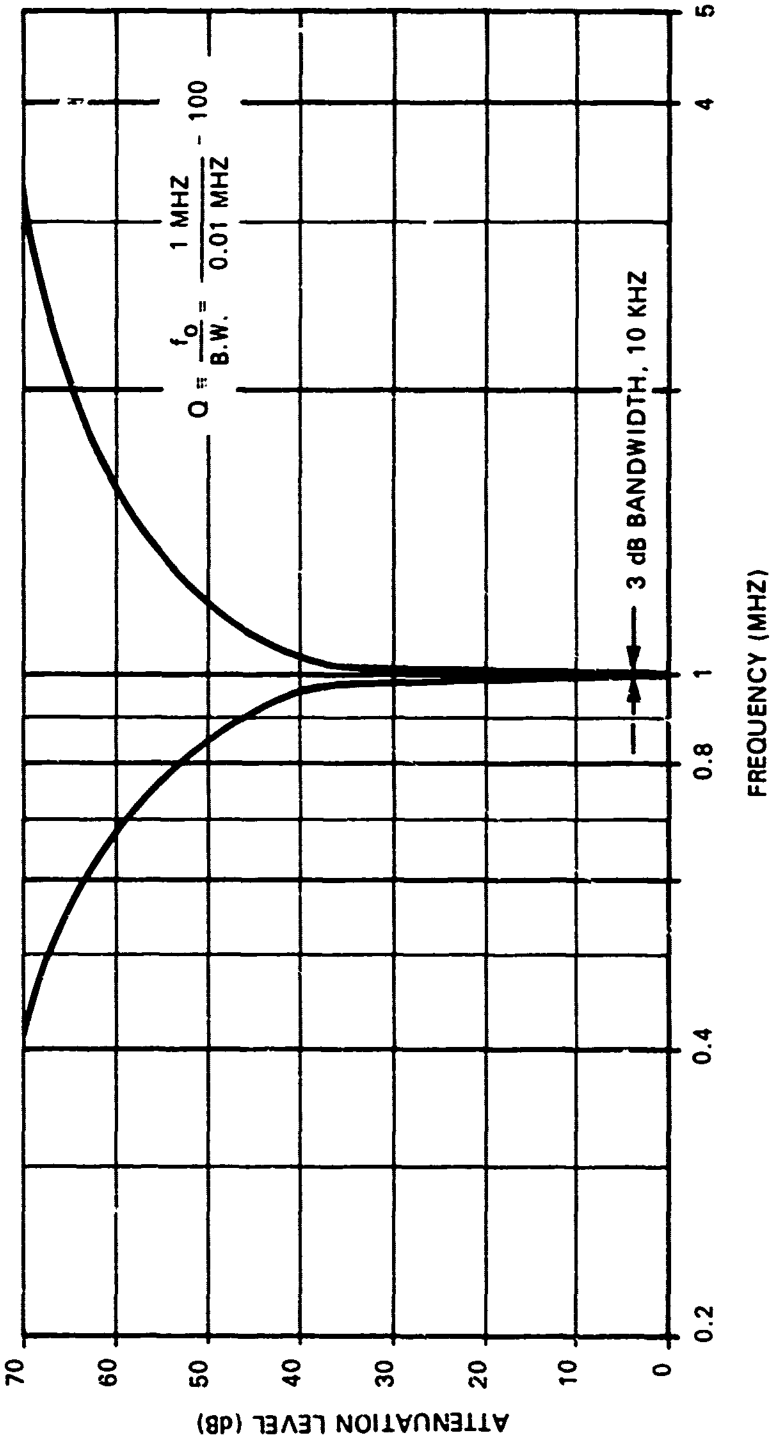


FIGURE 10-29 SELECTIVITY CURVE

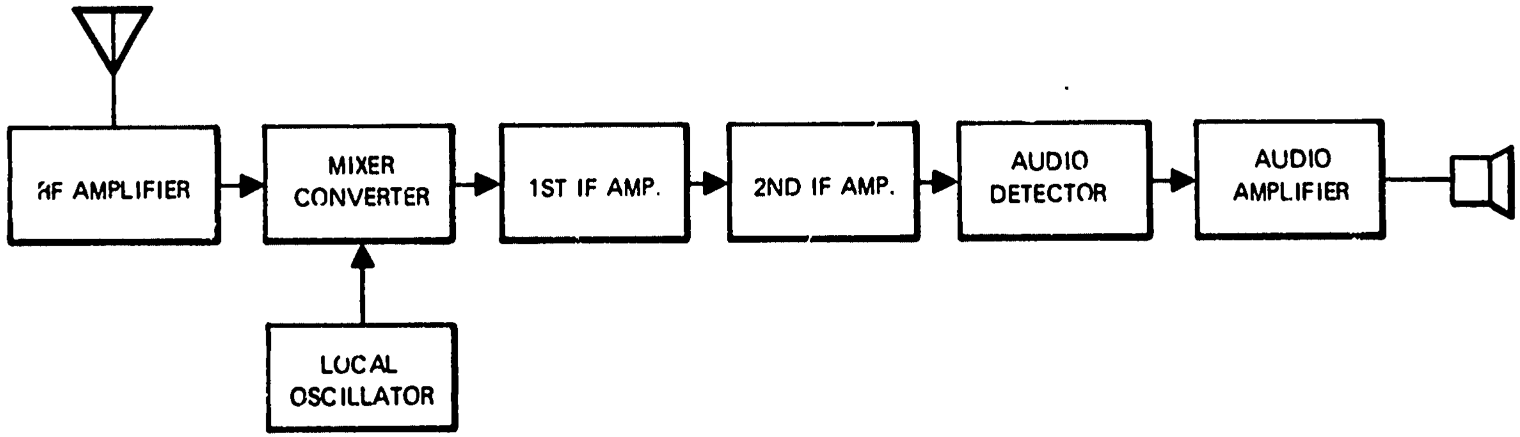


FIGURE 10-30 TYPICAL SUPERHETERODYNE RECEIVER BLOCK DIAGRAM

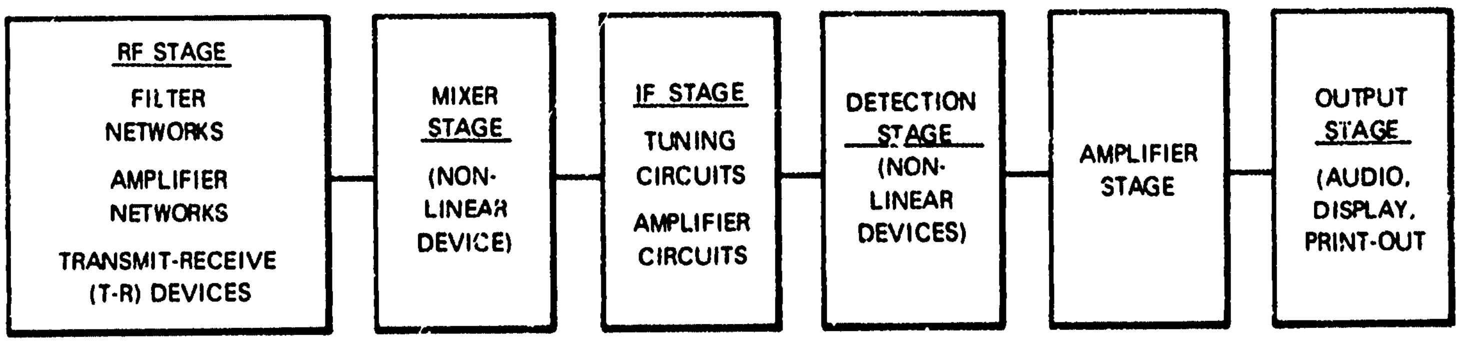


FIGURE 10-31 DIVISIONS OF TYPICAL COMMUNICATION OR RADAR RECEIVER

Frequency selective devices are widely used in communications and radar receivers. A functional block diagram of a typical superheterodyne receiver is given in Figure 10-30. The main portions of receivers are shown in Figure 10-31 as the RF stages, mixer, IF stages, detector, amplifier, and output stages. The RF stage can be composed of frequency selective devices, filters, amplifier circuits, and T-R (transmit-receive) devices.

Some receivers do not incorporate an RF amplifier. The frequency conversion stage usually consists of a local oscillator and a nonlinear mixing device. The IF (intermediate frequency) stages of the receiver, similar to the RF stages, contain tuning and amplifier circuits; but, because of frequency conversion in the mixer, the frequency has been reduced considerably to allow for better selectivity and amplification. The detector stage converts the IF to audio or video for further amplification. After the AF or video amplifier stage, the output stages may supply such functions as audio output, radar display, or print-out. If interference is present, the output stage is where the effect is most apparent. Interference can cause cross-talk, distortion, and character errors in communication systems or in radar-interfering patterns sometimes referred to as "running rabbits." Certain types of interference can also desensitize the receiver to the wanted signal without the interference itself appearing in the output.

Interference in receivers falls into three general categories: on-channel interference, adjacent channel interference, and spurious response interference. Each lends itself to different methods of reduction.

On-Channel Interference

The term "on-channel interference," sometimes called "cochannel interference," refers to the presence of interfering signals within the intended channel bandwidth of the system. Such signals can be caused by non-transmitting equipment noise, precipitation static, transmitter parasitics, EMC equipment, or unauthorized users of the frequency. Whatever the cause, the fact remains that there are interfering signals in the actual channel bandwidth. From the viewpoint of receiver design, since the interference is in the channel, nothing can be done to eliminate it. Suppressive measures or redesign can be applied to the source or sources when they are identified.

The effect of the interference can, however, be reduced by special techniques. Chief in importance among these is noise blanking. Blanking involves momentarily disabling the receiver during the presence of the interfering signal. It is primarily effective where the noise involved consists of short duration pulses. The technique has been applied to both communications and radar receivers.

Where the interfering signal comes from a radar on board the aircraft, a pulse obtained from the radar transmitter can be used as a keying signal for the blanker. If some form of unpredictable interference, such as precipitation static, is involved, it is often necessary to use a separate receiver operating on a nearby unassigned frequency to generate the blanking signal.

Blanking, however, cannot be successfully used where the duration of the blanking interval is such that it is deleterious to the system involved. In pulse

radar receivers, blanking in effect causes voids in the display, in which an incoming echo will not be seen. In communications receivers, a gap in the receiver output is produced. In voice systems, if the gap is relatively short, the effect of blanking on intelligibility is negligible, with the result that a noise blanker removes the interference with little cost. In a digital communications system, however, the blanker may cause one or more bits to be lost, with attendant consequences in the terminal equipment. A noise blanker, therefore, is not always applicable to the solution of a particular interference problem.

Another solution is to use what is known as hard modulation in the system. Modulation is hardened, i.e., made more immune to interfering effects, by taking advantage of redundancy. A hard modulation system usually either transmits less information per unit time or uses more bandwidth to transfer the same information. Examples of hard modulation include the use of wideband FM instead of AM, and frequency-shift keying instead of single-frequency keying.

The hardness of a modulation system is expressed in terms of the strength ratio between it and a specific interfering signal leading to a particular bit error rate or, in the case of voice signals, an articulation score. The resulting signal-to-interference ratio is termed a performance threshold. Ideally, above the threshold, the communications system will be free of interference, while below the threshold serious degradation from interference will result. The transition, however, is usually much more gradual than this, therefore, performance threshold data should be taken only as a guideline rather than a literal criterion. A listing of performance thresholds for several modulating schemes, in the presence of various unmodulated and modulated interfering signals, is given in Table 10-2.* The performance thresholds are given as the signal-to-interference ratio expressed in decibels. Thus, negative figures indicate that the interfering signal is stronger than the desired signal. These represent instances of a high immunity. Large positive figures, on the other hand, represent a relatively low immunity.

The performance threshold table is particularly useful in selecting a set of different modulation types that can share the same channel with a minimum of interference. A particularly advantageous situation results when the mutual interference between two modulation types is reciprocally low. An example of such an instance is operation of AM voice (A3) on a co-channel basis with pulse FM (FI). AM voice in the presence of FI interference has a threshold ratio of -23 dB, while FI in the presence of A3 has an interference ratio of -12 dB. It is interesting to note that the resulting shared situation is considerably better than if the channel had been shared by two signals of the same type, such as M3 versus A3 which has a performance threshold of -1 dB, while FI versus FI has a performance threshold of +6 dB.

Adjacent Channel Interference

Adjacent channel interference results from emission on the channels immediately on either side of the channel in use. Such interference may result from

*R. Mayher, ITT Research Institute "Basic Performance Thresholds", ECAC Report ESD-TR-66-9

unintended splatter from the transmitter or the adjacent channel. In this case, the interfering signal really is in the bandwidth of the receiver and little can be accomplished through receiver design.

If the interfering signal is strong, however, it is likely that the principal mode of interference is that resulting from simple overload of the receiver RF amplifier. The bandwidth of the RF amplifier is always in excess of the IF bandwidth and therefore includes not only the adjacent channel, but usually several others also. A strong signal can therefore cause this amplifier to operate in a nonlinear condition, the result being cross modulation, in which the intended signal is modulated by the adjacent interfering signal.

Nonlinear distortion also results in the formation of spurious intermodulation products. This aspect is discussed in the following section.

Adjacent channel or signals on other nearby frequencies can also result in a general desensitization of the receiver. This occurs when the signals become sufficiently strong to ride through the IF to the receiver AGC detector, which in turn reduces the gain of the receiver.

It is usually not possible to eliminate such proximity effects solely through receiver design. There are, however, several methods that can be used. One of the better methods is to use a high-Q wavetrap tuned to the frequency of the interfering signal, in shunt with the RF input of the receiver. At VHF and UHF, high-Q traps can be made using cavity resonators or transmission line stubs. At HF, MF, and LF the line can be shunted with a crystal filter. All shunt traps desensitize the receiver over a finite bandwidth. It must be recognized that performance of the receiver on the intended channel may be degraded by a trap tuned to a nearby frequency.

If the receiver is used only on one frequency, the high-Q trap can be connected in series with the line, so that it passes only the intended frequency.

Spurious Response Interference Modes

The Mixer

The vast majority of communications and non-communications receivers presently in use involve a design based on the superheterodyne principle, that is, frequency converters are used to establish one or more intermediate frequencies at which a high degree of selectivity is achieved by means of fixed tuned narrowband amplifiers.

Frequency conversion is used in communication and radar systems to generate a functional signal frequency such as the intermediate frequency in a receiver of the output frequency in a transmitter. In addition to the desired signal frequency, a group of undesired frequencies are formed that do not contribute to functional operation of the system and are therefore potential interference sources. Careful attention to design detail is needed to select the frequencies that will be least likely to cause EMI problems.

A nonlinear device can be defined as any device in which the output magnitude is not linearly proportional to the input. This includes devices in which the instantaneous output voltage is not proportional to the current or the

TABLE 10-2

ON-TUNE PERFORMANCE THRESHOLD

DESIRED DESIGNATION	UNDESIRED MODULATION DESCRIPTION	DESIGNATION SYSTEM PARAMETERS	BW_t	A1 =6kc/s $\delta_t=5$ PRF=50	A2 =6kc/s $m_t=1$	A3 =6kc/s $m_t=.5$ BABBLE	A3 =20kc/s $m_t=.3$ BABBLE	A3B =6kc/s BABBLE	A3J =3kc/s BABBLE	A4 =6kc/s $m_t=1$	A5C =6.25Mc/s $m_t=.7$	A9 >6kc/s $m_t=1$	F1 ≥6kc/s $\delta_m=5$	F2 =12kc/s $B_t=1$	F3 =12kc/s	F3 >>6kc/s	F4 =12kc/s $B_t=1$	F9 >>6kc/s	F9 >>6kc/s	P0 >>6kc/s $\delta_t=1/10$	P0D >>6kc/s	P0E >>6kc/s	P0F [illegible]	P0G [illegible]	P9 [illegible]	P9 [illegible]
A1	A1 PULSE	$BW_t=6kc/s$, $\delta_t=5$; $P_{FA}=10^{-4}$, $P_{D}=10^{-1}$	P_t 1	8		7	7	7	7	7	7	7	7	7	7	7	7	7	7	8	7	7	8	7	7	[illegible]
A2	AM 12 TONE FSK PULSE	$BW_t=6kc/s$, $m_t=1$; $P_{FA}=10^{-4}$, $\delta_m=5$	P_t 1%	9	6	0	0	11	7	6	11	11	5	6	6	11	11	11	11	9	6	6	6	9	6	6
A3	AM VOICE	$BW_t=6kc/s$, $m_t=.5$; 1000 word vocab	AS 50%	-23	-13	-1	-5	4	0	-13	0	2	-21	0	0	2	0	2	2	-23	-13	-13	-13	-23	-13	-13
A3	AM VOICE	$BW_t=20kc/s$, $m_t=1$; 1000 word vocab	AS 50	-19	-10	0	-4	7	3	-10	3	5	-19	3	3	5	3	5	5	-19	-10	-10	-10	-19	-10	10
A3B	2ND DSB SC VOICE or ANALOG	$BW_t=6kc/s$, 1000 word AS per channel	AS 50%	-36	-24	-7	-7	-7	-7	-24	3	3	-36	-7	-7	3	-7	3	3	-36	-24	-24	-24	-36	-24	-24
A3J	SSB SC VOICE or ANALOG	$BW_t=3kc/s$; 1000 word vocab	AS 50%	-36	-24	-7	-7	-7	-7	-24	3	3	-36	-7	-7	3	-7	3	3	-36	-24	-24	-24	-36	-24	-24
A4	AM FACSIMILE	$BW_t=6kc/s$, $m_t=1$; $(S/N)_o=10dB$	PER 50%	10	10	5	2	12	8	10	12	10	10	10	10	12	10	12	12	10	10	10	10	10	12	10
A5	TV VIDEO	$BW_t=6.25Mc/s$, $m_t=.7$; $(S/N)_o=13dB$	PER 90%	41	41	36	32	45	41	41	45	41	41	41	41	45	41	45	45	26	41	41	41	41	45	41
A9	AM ANALOG	$BW_t=6kc/s$, $m_t=1$; $(S/N)_o=10dB$	PER 90%	10	10	5	2	12	8	12	8	10	10	8	8	10	8	10	10	10	10	10	10	10	10	10
F1	FSK PULSE	$BW_t=12kc/s$, $B_t=1$; $(S/N)_t=13dB$	P_t 1%	6	-6	-12	-16	16	16	-6	16	16	6	-6	-6	16	-6	16	16	6	-6	-6	-6	6	[illegible]	[illegible]
F2	FM 12 TONE FSK PULSE	$BW_t=12kc/s$, $B_t=1$	P_t 1%	6	16	16	16	16	16	16	16	16	6	16	16	16	16	16	16	6	16	16	16	[illegible]	16	16
F3	FM VOICE	$BW_t=12kc/s$, $B_t=1$; 1000 word vocab	AS 50%	0	3	3	3	2	2	3	2	1	0	3	3	2	3	2	2	0	0	0	0	0	0	0
F3	FM VOICE	$BW_t=60kc/s$, $B_t=5$; 1000 word vocab	AS 50%	0	0	0	0	-4	-4	0	-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F4	FM FACSIMILE	$BW_t=12kc/s$, $B_t=1$; $(S/N)_o=10dB$	PER 50%	12	12	10	10	10	10	10	10	12	12	12	12	12	12	10	10	0	12	12	12	12	12	12
F9	FDM	n=No. of Channels; n≥2, n in dB	PER 50%	22+n	22+n	22+n	22+n	25	25	22+n	25	25	22+n	22+n	22+n	25	22+n	25	25	15	15	15	15	15	15	22+n
F9	FM ANALOG	$BW_t=12kc/s$, $B_t=1$; $(S/N)_o=10dB$	PER 90%	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
P0	PULSE (WIDE BAND)	$BW_t=12kc/s$, $\delta=1/10$; $P_{FA}=10^{-4}$ $P_{FD}=.5$	P_t 50%	5	7	7	4	10	10	7	7	7	7	7	7	7	7	7	7	10	10	10	10	10	10	[illegible]
P0D	PAM	n=No. of channels; n≥2, n in dB	PER 50%	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n	18+n
P0E	PWM	Threshold Criteria Single Edge Det	PER 50%	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
P0F	PPM	Threshold Criteria $(S/N)_o=12dB$	PER 50%	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
P0G	PULSE COMPRESSION	Threshold Criteria $(S/N)_o=12dB$	PER 50%	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
P9	MATCHED FILTER	$(BW_t/BW_o)=n$, n in dB, $(S/N)_o=10dB$	PER 90%	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n	10-n
P9	PHASE LOCK	22.5° Threshold Criteria	PER 50%	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13

derivative or integral of current. The impedance of these devices is not constant, but a function of current in the device. Some examples of nonlinear systems are crystal mixers, frequency multiplier circuits, frequency converters, modulators, magnetrons, klystrons, traveling-wave tubes, diode detectors, oscillators, and magnetic amplifiers. Most systems include one or more of the following three nonlinear elements: electron tubes, semi-conductors, and iron or ferromagnetic core inductances.

Most transfer functions can be represented as power series, and a nonlinear transfer function can be represented as:

$$I = a_0 + a_1 E + a_2 E^2 + a_3 E^3 + a_i E^i \qquad (10\text{-}12)$$

where:

I = instantaneous output current

E = instantaneous output voltage

a_i = constant coefficients whose values depend upon the particular shape of the transfer curve ($i = 0, 1, 2, 3$ ---)

The constant term a_0 can be neglected since it only causes a constant or DC shift in the curve to give:

$$I = a_1 E + a_2 E^2 + a_3 E^3 + \text{---} \qquad (10\text{-}13)$$

assuming an input signal of the form $E = A \cos(\omega_o t)$ is incidental upon the nonlinear element, and substitution of $A \cos(\omega_o t)$ into equation 10-11 gives:

$$I = a_1 A \cos \omega_o t + a_2 A^2 \cos^2 \omega_o t + a_3 A^3 \cos^3 \omega_o t + \text{---} \qquad (10\text{-}14)$$

By use of the trigonometric identity:

$$\cos(x) \cos(y) = 1/2 \left\{\cos(x + y) + \cos(x - y)\right\}$$

and combining terms yields:

$$I = C_0 + C_1 \cos \omega_o t + C_2 \cos^2 \omega_o t + C_3 \cos^3 \omega_o t + \text{-------} \qquad (10\text{-}15)$$

where:

$$C_0 = 1/2 a A^2 + 1/8 a_x A^4 + \text{--------}$$

and

$$C_n = \sum_{i=n}^{\infty} \left\{1 + (-1)^{n+i}\right\} a_i \left(\frac{A}{2}\right) i \qquad \text{for } n = 1,2,3 \text{ ---}$$

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Equation 10-15 shows that the output current from a nonlinear device is composed of a term containing the original input frequency, ω_o, and all its harmonics.

For two input signals incident upon the nonlinear elements, the components input signal can be represented as:

$$E = A \cos \omega_1 t + B \cos \omega_2 t \qquad (10\text{-}16)$$

where:

E = instantaneous input voltage to the nonlinear element

A = maximum amplitude at the input to the nonlinear element of one of the incoming signals

B = maximum amplitude at the input to the nonlinear element of a second incoming signal

ω_i = angular frequency of the incoming signals (i = 1 or 2)

Substituting equation 10-16 into equation 10-13, the expression for output from the nonlinear elements becomes:

$$I = a_1(A \cos \omega_1 t + B \cos \omega_2 t) + a_2(A \cos \omega_1 t + B \cos \omega_2 t)^2$$

$$+ a_3(A \cos \omega_1 t + B \cos \omega_2 t)^3 + \text{---------} \qquad (10\text{-}17)$$

After multiplying and applying the trigonometric identity, the output current expression from the nonlinear element becomes:

$$I = C_0 + C_1 \cos \omega_1 t + C_2 \cos \omega_2 t$$

$$+ C_3 \cos 2\omega_1 + C_4 \cos^2 \omega_2 t$$

$$+ C_5 \cos (\omega_1 \omega_2)t + C_6 \cos (\omega_1 + \omega_2)t$$

$$+ C_7 \cos (2\omega_1 - \omega_2)t + C_8 \cos (2\omega_1 + \omega_2)t$$

$$+ C_9 \cos (\omega_1 - 2\omega_2)t + C_{10} \cos (\omega_1 + 2\omega_2)t$$

$$+ C_{11} \cos 3\omega_1 + C_{12} \cos 3\omega_2 + \text{-------------} \qquad (10\text{-}18)$$

Equation 10-18 indicates that the output current from a nonlinear element is made up of all orders of the frequencies of the two input signal frequencies. Thus, the output signal has frequency components that satisfy the expression:

$$f_0 = |mf_1 \pm nf_2| \qquad (10\text{-}19)$$

where:

f_0 = frequency component of output signals

f_i = input signal frequency (i = 1 or 2)

m = 0, 1, 2 ------------

n = 0, 1, 2 ----------

Each m and n expresses the frequency of an intermodulation product of the two input signals at the output of the nonlinear elements. This equation is known as the law of the mixer.

The general equation for any number of input signal frequencies would be:

$$f_0 = |m_1 f_1 \pm m_2 f_2 \pm \cdot \cdot \cdot| \qquad (10\text{-}20)$$

where:

f_0 = output frequency from nonlinear element

f_i = *ith* input frequency (i = 1, 2, 3 ---)

m_i = 0, 1, 2, --- for each i = 1, 2, 3 --- (integers only)

Equation 10-20 shows that all possible combinations of the input signal frequencies, including harmonics of each frequency, are present at the output of a nonlinear element. This phenomenon is used to convert signals from RF to the operating frequency of the IF amplifiers in most receivers. The undesirable effect from this method of frequency generation is the accompanying generation of undesired nonfunctional frequencies.

Figure 10-32 illustrates a nomograph that can aid in the design of mixers. The vertical scale of the graph is expressed in terms of f_0/f_2 where f_0 is the output frequency and f_2 is one of the two input frequencies. The horizontal scale is calibrated in terms of f_1/f_2 where f_2 is the remaining input frequencies. The lines on the graph represent the first 10 orders of mixer components. The order of the component is defined as the sum of the integers m and n in equation 10-20, which are responsible for its formation. Thus, there are 20 possible 10th order components corresponding to:

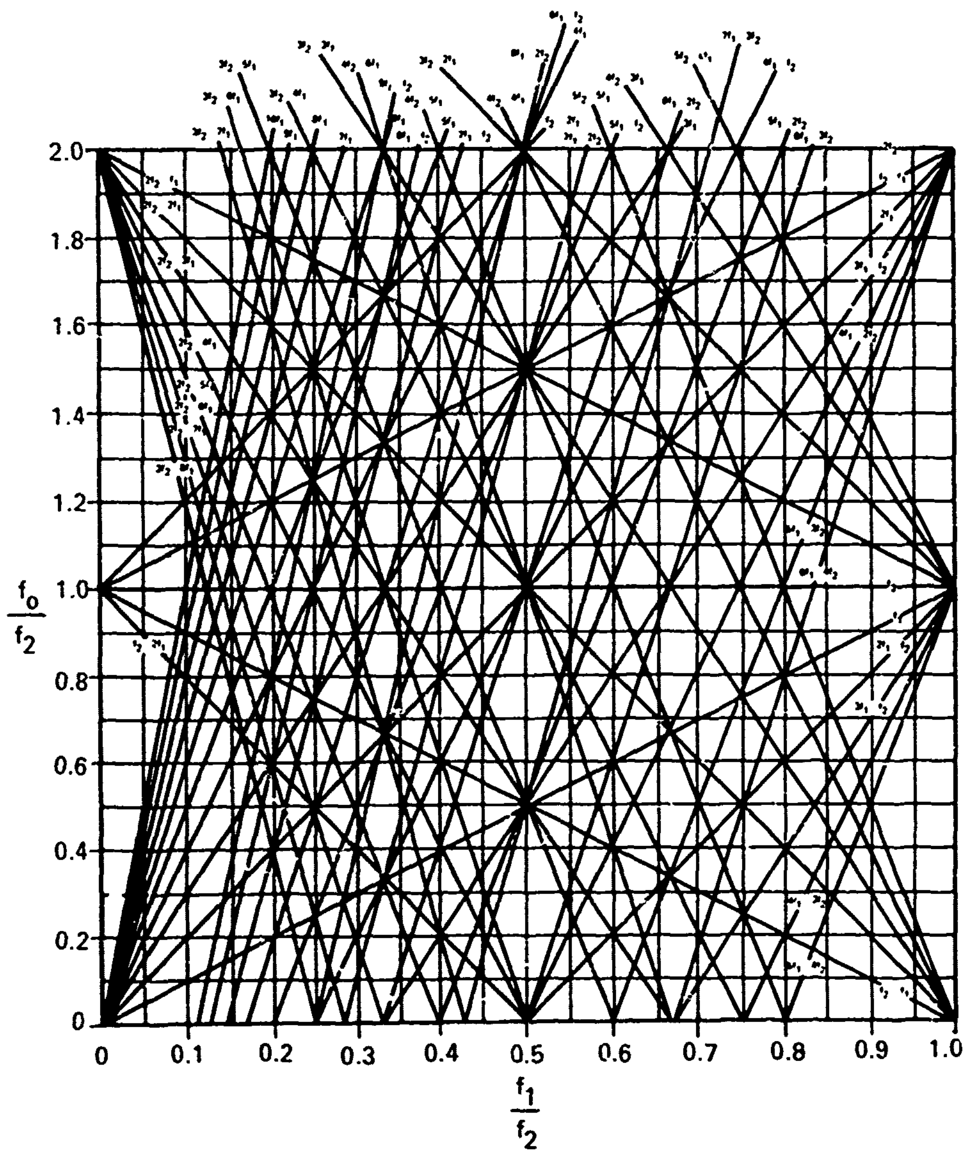


FIGURE 10-32 MIXER CHART, WITH f_1 AND f_2 AS MIXER INPUT FREQUENCIES ($f_2 > f_1$) f_o AS DESIRED OUTPUT FREQUENCY. (LINES INTERSECTED WHEN TRACING STRAIGHT UP FROM VALUE OF f_1/f_2 REPRESENT COMBINATION FREQUENCIES, VALUES OF WHICH CAN BE FOUND EITHER FROM LABELS ON LINES OR FROM SCALE ORDINATES. ONLY INTERSECTIONS NEAR DESIRED COMBINATION (SUM OR DIFFERENCE) NEED BE CONSIDERED.) REF. T. T. BROWN, ELECTRONICS, JUNE 1954.

$f_0 = 10f_1$ (In practice, the sum components are far from the intended output frequency. Therefore sum components above the third order are omitted from the chart. Accordingly, 11 tenth-order component equipment lines are shown.)

$f_0 = 10f_2$

$f_0 = 9f_1 \pm f_2$	$f_0 = 6f_1 \pm 4f_2$	$f_0 = 3f_1 \pm 7f_2$
$f_0 = 8f_1 \pm 2f_2$	$f_0 = 5f_1 \pm 5f_2$	$f_0 = 2f_1 \pm 8f_2$
$f_0 = 7f_1 \pm 3f_2$	$f_0 = 4f_1 \pm 6f_2$	$f_0 = f_1 \pm 9f_2$

The magnitude of the remaining components is dependent on the conversion gain of the mixer and the characteristics of the filter used following the mixer. The mixer conversion characteristic is usually such that each succeeding order product is 6 dB below its antecedent; that is, all third order products will be 6 dB below the second order products, which are in turn 6 dB below the weaker of the two input signals f_1 or f_2.

The mixer chart is used by first selecting and locating the line of the desired output component. Most receivers use the difference component, $f_2 - f_1$. Then the ratio of the two input frequencies is selected. Suppose, for example, reception of a 1 MHz signal is desired at an IF output frequency of 250 kHz. The ratio will then be 0.75. Other output components f_1/f_2 are found by tracing up the vertical line from 0.75 on the f_1/f_2 scale and noting the reading on the f_0/f_2 scale corresponding to the intersections with the neighboring component lines. Those components dependent on the design of the output filter are the most significant spurious-output components. In general, the best mixer is one in which nearby intersecting lines do not correspond to low-order products. When nonlinear frequency generation is used, some design or suppression techniques must be used to reduce unwanted signals to appropriate levels.

Image Response

Most C-E receivers incorporate a signal mixing process using nonlinear devices to convert RF signals to a lower intermediate frequency (IF) for easier accomplishment of amplification and selectivity. When two signals are combined in a nonlinear element to produce a third signal, the process is called heterodyning. An internally generated local oscillator frequency is higher than the receiver tuned frequency. The expression for the IF frequency is:

$$f_{IF} = f_{LO} - f_o \qquad (10\text{-}21)$$

where:

f_{IF} = intermediate frequency

f_{LO} = local oscillator frequency

f_o = receiver tuned frequency

If an undesired interference frequency (f_i) is received that is greater than the local oscillator frequency (f_{LO}) by an amount equal to the IF, an undesired signal at the IF frequency is produced as follows:

$$f_{IF} = f_i - f_{LO} \tag{10-22}$$

The undesired frequency (f_i) is known as the image frequency. This image frequency can be above or below the local oscillator frequency by the IF, but is on the opposite side of the local oscillator frequency from the desired tuned frequency (f_i is below the f_{LO} if the desired tuned frequency is above f_{LO}). Because harmonics of the incoming signal and local oscillator are produced in the nonlinear device in addition to all sums and differences of all harmonics, a large number of spurious frequencies can be generated. Some of these may fall within the passband of the IF portion of the receiver. The frequencies at which these spurious responses occur can be determined from a general form of equation:

$$f_{sp} = \frac{|pf_{LO} \pm f_{IF}|}{q} \tag{10-23}$$

where:

f_{sp} = spurious response frequency

f_{LO} = local oscillator frequency

f_{IF} = intermediate frequency

p = zero or an integer denoting the harmonic order of the local oscillator. When p=o direct feed-through to the IF amplifier is indicated as the response mechanism

q = an integer (not zero) denoting the harmonic order of the received spurious frequency

Since receivers are generally designed to respond to either the second-order sum or difference components, there are three different operating configurations corresponding to:

a. $f_{LO} = f_{IF} + f_d$;

b. $f_{LO} = f_d - f_{IF}$;

c. $f_{LO} = f_{IF} - f_d$;

where f_d is the receiver dial setting, that is, frequency of desired signal.

In general, unless the interfering signal has a very strong q, equation 10-23 will be one indicating that the response is not due to a harmonic of the input

signal. The equation then becomes

$$f_{SP} = pf_{LO} \pm f_{IF} \tag{10-24}$$

It is possible to construct graphs that illustrate the spurious response frequencies as a function of receiver dial settings. Figure 10-33 illustrates the form of that resulting from case a. above, which is the configuration most commonly used in down conversion.

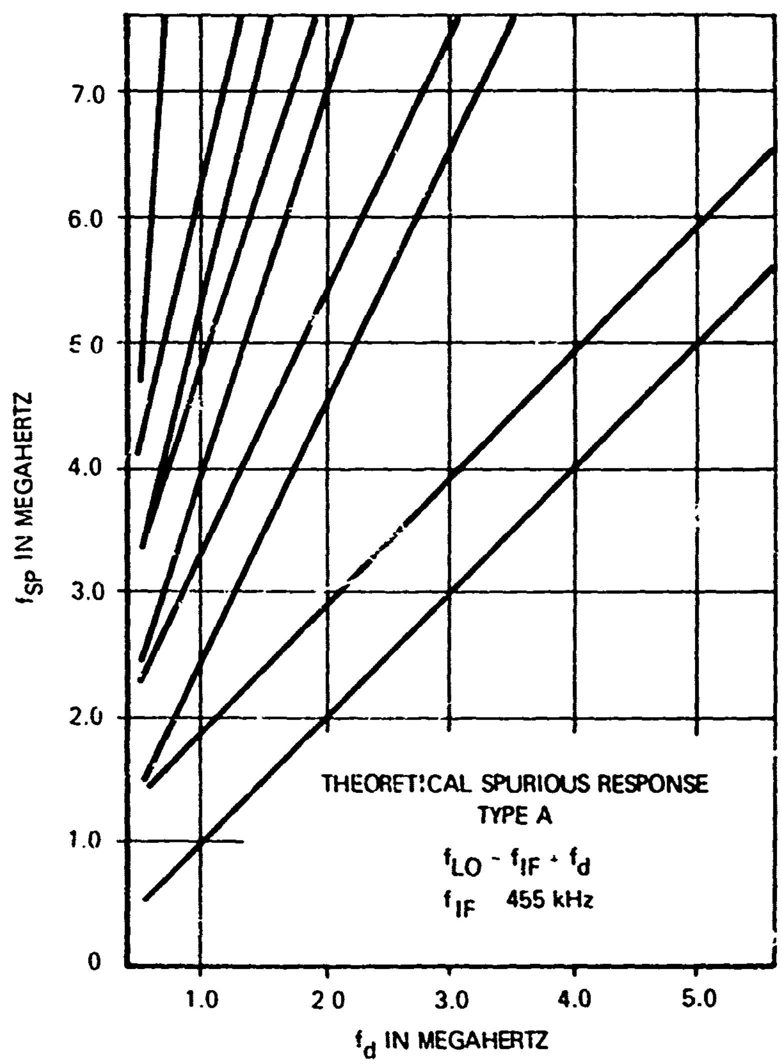


FIGURE 10-33 THEORETICAL SPURIOUS RESPONSE, TYPE a, IF = 455 kHz

Figure 10-34 shows the form of the curves which result from configuration b. and Figure 10-35 illustrates the result of case c.

The solution to the spurious response problem lies in designing the receiver RF amplifier so that its passband is sufficiently narrow to attenuate the nearest image frequency. Since filter designs of necessity yield a bandpass proportional to tuned frequency, it is often not possible to achieve a narrow bandwidth with a practical design. In this case, it is necessary to use a higher IF frequency, which causes the image frequency to fall further from the receiver tuned frequency. This is one of the primary reasons that most HF, VHF, and UHF receivers use multiple conversion schemes.

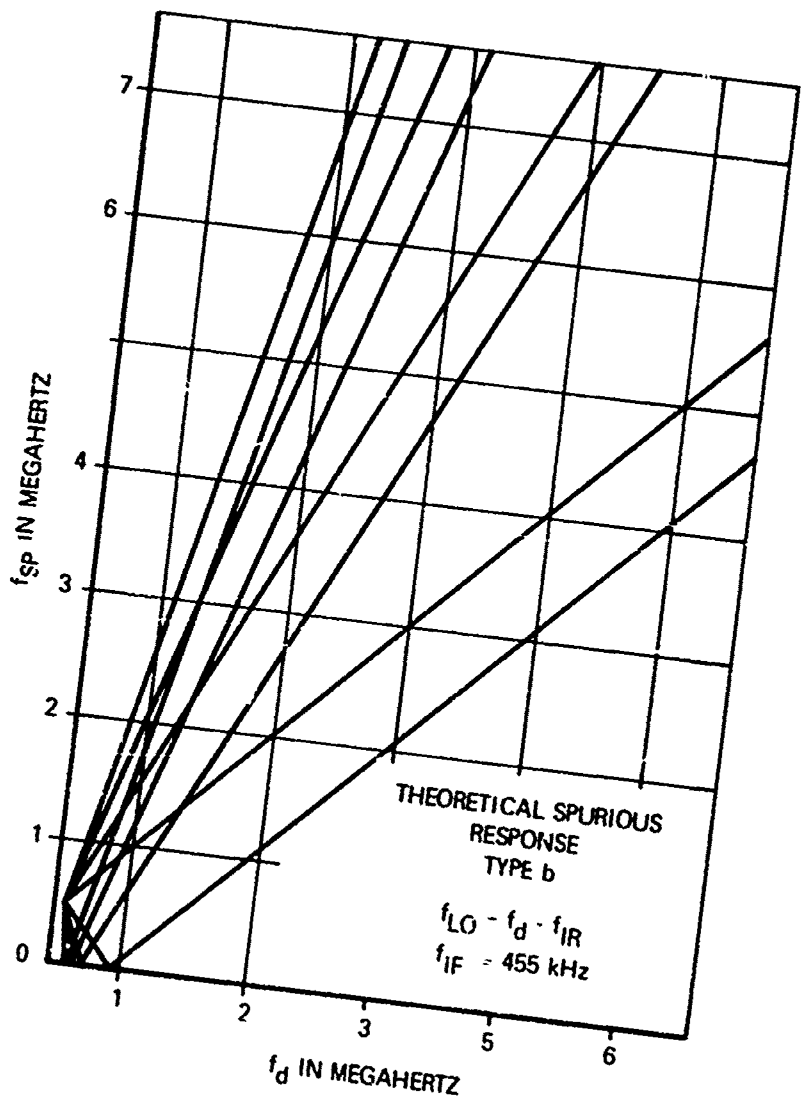


FIGURE 10-34 THEORETICAL SPURIOUS RESPONSE, TYPE B, IF = 455 kHz

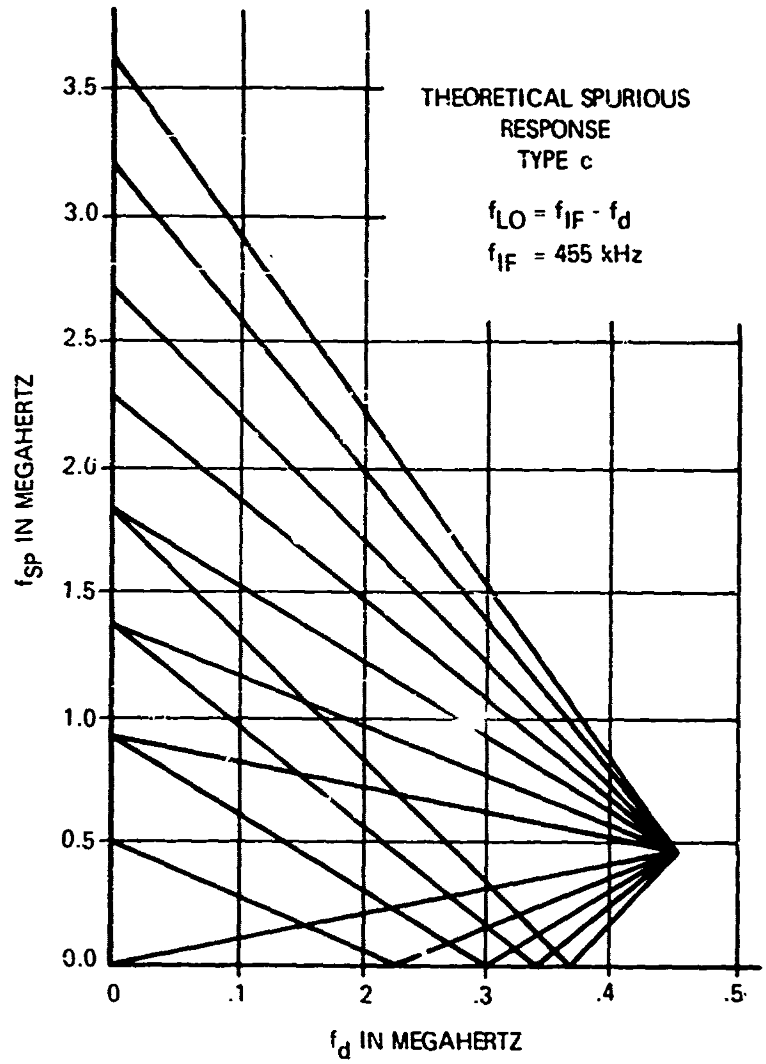


FIGURE 10-35. THEORETICAL SPURIOUS RESPONSE, TYPE C, IF = 455 kHz

Intermodulation

Another form of frequency conversion is intermodulation, in which two or more frequencies are combined or intermodulated in some nonlinear circuit to produce new frequencies equal to the sum and differences of the integral multiples of the original signal frequencies.

A receiver stage may become nonlinear because of strong signals being applied to some circuit element, either active or passible, which exceeds the capability of that circuit element to process the signal in a linear manner. Solid state or vacuum tube amplifiers are the common victims, although ferrite cores

driven into magnetic saturation exhibit the same characteristic. Less common nonlinear admission mechanisms involve imperfect joints between conductors ahead of the receiver filter circuits, which result in nonlinear junction effects. Except in unusual cases, the level of input signal required to create an intermodulation effect in the presence of a desired signal is several tens of decibels greater than the desired signal; that is, the undesired signal level required to register an effect is generally such that local transmitters are usually the only significant sources. Sources not intended to radiate, spurious outputs of transmitters, and broadband noise sources are rarely found to be important in these modes. There are exceptions, however, so that such possibilities must not be dismissed without some examination of the environment.

Spurious responses of a receiver due to nonlinear mechanisms will most often be the result of nonlinearity in an early stage, which is driven into nonlinearity by the intruding interference. The situation is most exasperating because at each frequency of tuning, another set of possible spurious response frequencies exist and each of these sets has its own level of significance. Audio stages that employ high impedance inputs and/or outputs are also likely victims.

If two or more signal carriers mix in a nonlinear device, spurious components are generated at one or more frequencies that are not equal to the original frequencies. Usually the unwanted signals appear together at the receiver input where they are acted upon by the input amplifier, which has some degree of nonlinearity. The situation arises mainly when a range of frequencies is subdivided into separate communication channels and when a number of these channels, which are closely spaced, must be used simultaneously, causing strong signals to appear within the bandwidth of the receiver RF amplifier.

For instance, two signals of the form:

$$x_1(t) = V_1(t) \cos \left\{\omega_1 t + \phi_1(t)\right\} \tag{10-25}$$

and

$$x_2(t) = V_2(t) \cos \left\{\omega_2 t + \phi_2(t)\right\} \tag{10-26}$$

will produce the following components due to the third-degree term of the power series representing the nonlinearity:

$$\begin{aligned} y_1(t) = V_1^2(t)V_2(t) \Big\{ & 1/2 \cos \left[\omega_2(t) + \phi_2(t)\right] \\ & + 1/4 \cos \left[(2\omega_1 + \omega_2) \quad 2\phi_1(t) + \phi_2(t)\right] \\ & + 1/4 \cos \left[(2\omega_1 - \omega_2)t + 2\phi_1(t) - \phi_2(t)\right]\Big\} \end{aligned} \tag{10-27}$$

The last two components are the intermodulation terms. The last one is usually the troublesome one, since it is at a frequency close to both ω_1 and ω_2. For example, suppose that a service has available the range of frequencies from

100 to 110 MHz which is sub-divided into 1-MHz channels. If one transmitter were operating at 100 MHz and another were at 102 MHz, an intermodulation component would exist at 2(102) - 100 = 104 MHz.

A local receiver tuned to receive 104 MHz is vulnerable to this component. In a confined environment, special effort would have to be made to reduce the intermodulation or to avoid the use of certain channels. In addition to the frequency $(2\omega_1 - \omega_2)$, $(2\omega_2 - \omega_1)$ will also be troublesome.

It will similarly be found that with three channels at frequencies f_1, f_2, and f_3, intermodulation products of the kind discussed above (that is, those products near in frequency to the original generating frequencies but not coincident with them), are:

a.	$f_1 + f_2 - f_3$	e.	$2f_2 - f_1$
b.	$f_1 - f_2 + f_3$	f.	$2f_2 - f_3$
c.	$2f_1 - f_2$	g.	$2f_3 - f_1$
d.	$2f_1 - f_3$	h.	$2f_3 - f_2$

The even-degree terms in the output-input Taylor's expansions also give rise to intermodulation components, but they are all far from the range of frequencies in question. Though the third-degree term is generally the most important, the fifth-degree term may have to be accounted for also. Possible interference components due to fifth-degree nonlinearity are:

a.	$f_1 + f_2 + f_3 - f_4 - f_5$	d.	$2f_1 + f_2 - 2f_3$
b.	$2f_1 + f_2 - f_3 - f_4$	e.	$3f_1 - f_2 - f_3$
c.	$f_1 + f_2 + f_3 - 2f_4$	f.	$3f_1 - 2f_2$

These are only representative forms; the subscripts on the frequencies above may be permuted in any way among the assigned frequencies. Thus, if there are 10 frequencies, $3f_7 - 2f_{10}$, or $f_1 - f_2 + f_3 - f_4 + f_9$, are frequencies that can be significant.

Techniques for channel selection to avoid interference are given by Babcock and by Beauchamp (See References).

Tests of vulnerability to intermodulation in actual receivers have been described in detail. McLenon applied signals to commercial grade receivers to give potential intermodulation at 5.1 MHz. He obtained a resultant interference carrier level of 0.5 volt for inputs ranging from 0.01 volt to 0.1 volt. The highest input was required in a receiver that had two tuned circuits before the first amplifier tube.

A sample calculation of the magnitude of intermodulation interference follows. Third-degree nonlinearity is assumed, where the coefficient of the third-

degree term in the Taylor series is a_3. The output interference component is then:

$$Y_1(t) = \frac{3a_3}{4} V_1^2(t) V_2(t) \cos(2\omega_1 - \omega_2)t \tag{10-28}$$

where:

$(2\omega_1 - \omega_2) = \omega_o$ is the tuned frequency of the receiver. A desired signal, $x_s(t) = V_s(t) \cos \omega_o t$, entering the receiver at the same time will result in an output term determined by the first-degree term (with coefficient a_1) of the Taylor series. Thus, $y_s(t) = a_1 v_s(t) \cos \omega_o t$.

The signal-to-interference ratio is defined as the ratio of the coefficients of these two waves:

$$\frac{S}{I} = \frac{4a_1 v_s(t)}{3a_3 v_1 2(t) v_2(t)} \tag{10-29}$$

If, for simplicity, $v_1(t)$, $v_2(t)$, and $v_s(t)$ are taken as constants, v_1, v_2, and v_s, respectively, and the two unwanted signal amplitudes are assumed equal so that $v_1 = v_2$, then the signal-to-interference ratio is unity when:

$$v_1 = \frac{4a_1 v_s 1/3}{3a_3} \tag{10-30}$$

If, for instance,

$v_s = 10 \times 10^{-6}$ volt

$a_1 = 5 \times 10^{-3}$ mho

$a_3 = 5 \times 10^{-5}$ amper/volt^3

then $v_1 = 0.11$ volt. At VHF a spacing of about 150 feet between the transmitting and receiving antennas, assuming a 50-watt transmitter, will give such a value.

The v_1 is the amplitude at the input to the nonlinear element, but the amplitude at the antenna terminals will be greater than this figure. Usually, the selectivity of the input circuit is not sufficient to cause much attenuation to the unwanted signals. The input unwanted signal voltage is thus somewhat greater than 0.11 volt.

Receiver intermodulation is the combining of two or more unwanted signals, or multiples of these signals, in a nonlinear element in the receiver. The most likely locations of nonlinear elements are in the RF amplifier stages or the mixer. The most serious form of receiver intermodulation is the third-order difference intermodulation product, because both signals that are combined may fall within the passband of the receiver's input circuits. Third-order difference intermodulation products are computed as follows:

$$f_0 = |2f_1 - f_2| \tag{10-31}$$

where:

f_0 = receiver tuned frequency

f_1 and f_2 = two unintentionally received or generated signals

Second and higher order intermodulation products are possible interfering signals, but the higher order products are much smaller in amplitude relative to lower order products. The intermodulation order is calculated by addition of the integers multiplying each interfering frequency. More than two frequencies can combine to form intermodulation frequencies in methods similar to two-frequency intermodulation.

Cross Modulation

Transfer of information can be performed by modulating or superimposing an information-bearing signal on a carrier signal. Amplitude modulation varies the total amplitude of the signal power, and frequency modulation varies the frequency of the carrier, while total signal amplitude remains constant. Cross modulation occurs when two signals, one of which is the desired signal, are received by a receiving device and the modulation of one is combined with the other by intermodulation in a nonlinear element. In audio circuits, cross modulation or transfer of modulation from the unwanted signal to the desired signal is referred to as cross-talk. In cross modulation, the unwanted signal is attenuated very little in comparison to other intermodulation frequencies. If the unwanted signal is strong enough or contains extreme variations in modulation, receiver desensitization may occur in addition to the cross modulation effects.

IF Responses

One of the principal mechanisms of spurious receiver interference is coupling of a signal directly into the receiver IF strip. The usual source of such a signal is a nearby transmitter operating at the receiver IF frequency. For example, many VHF receivers use an intermediate frequency of 10.7 MHz. If a transmitter is operated on this frequency or has a spurious output on this frequency and the shielding of the receiver is insufficient, interference will probably occur.

The chief characteristic of such interference is that it is nontunable, that is, it occurs at all receiver tuned frequencies and on all bands. The interference is caused by the existence of an extraneous coupling path to the IF amplifier. The usual mechanism is poor shielding, poor component layout, inadequate filtering, or defective grounding procedures within the receiver.

In systems design of naval aircraft systems, it is good practice to avoid the

use of receiver intermediate frequencies on transmission channels. If, however, this is unavoidable, the problem can be minimized by taking appropriate precautions in receiver design.

In retrofit design it is difficult to alleviate IF interference because a complete redesign of internal shielding is necessary.

In some instances, the interfering signal is coupled through the receiver input, or through the powerline, and the receiver shielding is not at fault. In these instances the difficulty can be minimized or alleviated by external power line filtering or through the use in the antenna input line of a wavetrap tuned to the intermediate frequency.

Broadband Interference

The term "broadband interference" is applied to any interfering signal the bandwidth of which is in excess of the receiver channel bandwidth. The usual forms of such interference is pulse, impulse, or random noise.

The degree to which such interference constitutes an EMC hazard depends on the amount of energy present within the channel. This can be computed by determining the spectral intensity of the noise using the analysis methods outlined elsewhere.

The effect of the noise on the receiver is somewhat similar to both co-channel and adjacent channel interference. The co-channel aspect of the signal acts to reduce sensitivity and causes bit errors, low articulation scores, etc., to a degree dependent on the type and strength of the noise and the type of modulation system being used. The adjacent channel aspect of the noise can, if sufficiently strong, produce spurious products.

In systems design, the best approach is to contain or eliminate the noise at the source by shielding and frequency allocation. Often, however, the source of the noise is from a remote source not within the system or from a mechanism such as precipitation static that cannot be eliminated through design. Moreover, the noise may come from a higher priority source such as the fire control radar, which cannot be changed to another frequency.

In the above circumstances, only three solutions are available. For the first alternative, the receiver frequency can be moved to another if it is determined that another frequency having less noise is available.

Secondly, the coupling between the offending transmitter and receiver can be reduced by judicious antenna placement, such as radar in the front of the aircraft, receiver in the rear.

If the above two methods do not alleviate the interference, noise blankers may help. (The use of noise blankers is described in the section entitled "On-Channel Interference.")

Another approach is to make sure that the narrowest possible bandwidth is used in the receiver, commensurate with the intended purpose of the channel. Narrowing the bandwidth increases the signal-to-noise ratio as long as the bandwidth is less than that of the noise and more than that occupied by the desired signal. The degree of improvement depends on the spectrum of the noise.

Impulse noise is uniformly distributed in frequency: therefore, the improvement resulting from the use of a narrower band is directly proportional to the normalized bandwidth reduction. For random noise, the improvement in signal-to-noise ratio is proportional to the square root of the normalized bandwidth reduction.

Interference Margins and Statistical Parameters

The interference levels caused within a co-sited group of transmitters and receivers from causes within the system is a complex function of the transmitter intended and spurious outputs, the receiver spurious responses, and the mutual coupling applicable to a given interference mode. Where a computation of service probability is desired, additional information relative to the intended communication or radar channel becomes a part of the computation, since this defines the received level of the intended signal. The parameters needed in the calculation include the transmitted power, transmitter antenna gain, path loss, receiver antenna gain, and receiver sensitivity.

All of these quantities for a particular system are well known constants, with the exception of the path loss. Path loss, unless free space propagation prevails, is a time-varying quantity, being dependent on such variables as absorption, ionospheric reflection, and refraction index.

In the section entitled "Interference Generating Sources," methods for determining the power output spectrum of a transmitter were given. The result was expressed in dB referred to the fundamental at the output terminals. This is not, however, representative of the actual power radiated from the transmitting system.

The power radiated from the antenna is given by

$$P_T + G_T - C_T \qquad (10\text{-}32)$$

where:

P_T is the power spectrum output of the transmitter

G_T is the transmitting antenna gain

C_T is the coupling loss between the transmitter and the antenna.

All three of the above are functions of frequency.

The power density available at the receiver due to the emissions of the transmitter is given by:

$$P_T + G_T - C_T - L \qquad (10\text{-}33)$$

where L is the total propagation loss of the transmission path.

In a similar manner, the power P_R, necessary to cause a spurious response or otherwise interfere with a receiver, can be expressed as a function of frequency. When the interference in question is due to the signal at the RF input, the level at tne receiving antenna necessary to cause interference can be expressed as:

$$P_R - G_R + C_R \tag{10-34}$$

where:

P_R is the power needed to cause interference at the input

G_R is the gain of the receiving antenna

C_R is the coupling loss between the antenna and the receiver input all expressed in dB

If the power at the receiving antenna due to the transmitter is greater than that necessary to cause interference, degradation results. This condition obtains when

$$P_T + G_R - C_T - L > P_R - G_R + C_R \tag{10-35}$$

or

$$P_T - P_R + G_T + G_R - C_T - C_R - L > 0$$

All of the terms in this equation are functions of frequency. Most are also functions of other parameters and are statistical in nature. This is particularly true of path losses and the other variables to the extent that levels are different, depending on adjustment of equipment; positioning of antennas, and other variables.

Analyzing and predicting interference and evaluating the effect on victimized systems must, in some fashion, take these statistical characteristics into account.

DESIGN OF SYSTEMS FOR EMC

GENERAL

In the design phase of systems and subsystems, several methods may be used at the system level to reduce the degree of EMC hazard. The primary methods consist of analysis of system and subsystem operating configurations with regard to the frequency and length of system or subsystem use, allocation of system and subsystem functional frequencies, and use of hard modulation schemes to the maximum extent feasible. Other applicable factors include the physical arrangement of systems and subsystem equipment units within the aircraft.

TIME AND FREQUENCY FACTORS

Time and frequency factors are those derived from the system and subsystem time domain operating requirements. These factors relate to the frequency of use of each subsystem equipment and the duration of each use. Time and frequency factors are thus derived from and closely interwoven with the overall mission of the aircraft.

Analysis of equipment use period is necessitated whenever it becomes obvious that equipments in different subsystems are mutually incompatible, that is, the operation of one degrades the performance of the other. If the interference is considered hazardous, the extent to which one system is used at the same time as the other becomes an important factor. This factor is determined on the basis of the role of each in overall aircraft operations. For example, the operation of many equipments is intermittent rather than continuous. Such equipments, while part of a subsystem, are not in operation for the same period of time as the entire subsystem. An example of such an equipment is a communications transmitter. It is not used continuously, and futhermore, may not necessarily emit on the same frequency in each use. The victim equipment may similarly be only in sporadic use for brief periods.

Individual equipment usage is therefore statistical in nature and can be treated theoretically by computing the probability that two interfering equipments will be in operation simultaneously. The same type of analysis can be extended to the cases similar to the transmitter cited above, which causes interference only in certain modes of operation.

Whenever, on the basis of usage analysis, there is a high probability of interference, the equipment complement must be revised or the mission scenario recomposed so that the interference is reduced or eliminated.

ALLOCATION OF FREQUENCIES

Interference can be reduced or eliminated through proper assignment of frequencies occupied by communications, radar, and other transmitted and functional signals. Implicit in frequency allocation is knowledge of the bandwidths occupied by all intentional and spurious signals as well as receiver spurious

response characteristics. Where the latter coincide with fundamental or spurious functional signals, there is likely to be interference.

Frequency allocations must also consider such effects as broadband receiver desensitization caused by nearby transmitters.

Allocation techniques can be applied both during the equipment design phase and whenever a system configured of existing equipments is being planned. One example of the use of frequency allocation in the equipment design phase of transmitters is the avoidance of certain well known receiver intermediate frequencies such as 455 kHz, 10.7 MHz, and 21.4 MHz, when selecting the frequencies of high level functional signals. Where a system is being composed of existing equipments, data related to intentional and spurious output frequencies and spurious response frequencies are examined with a view toward avoiding incompatible equipment combinations.

The domain of frequency allocation techniques is not confined solely to systems within a single aircraft. It is especially important that in the selection of communications and radar transmitting frequencies, the usage of these frequencies by other aircraft, ground, and ship stations be considered, since the coverage area of an airborne transmitter may be quite large and can cause severe interference to other systems.

MODULATION HARDENING

It has been established through theoretical studies and practical experience that certain forms of modulation are relatively immune to interference from particular types of noise and other signals using different types of modulation. Comparisons between modulation schemes are made by evaluating quantitatively the degradation due to given levels of the interfering signal expressed in terms of such measures as bit error rates and articulation indices. Data related to the relative hardness of various forms of modulation are included in the section entitled "Interference Margins and Statistical Parameters."

In system design the need for modulation hardening is indicated when interference to communications systems from radar transmitters and other sources is so severe that significant degradation is caused to the particular communications system. It is often possible to fulfill the communications need equivalently with a system using a different form of modulation upon which the interference has a less degrading influence. Such systems usually, however, are more complex, often involving conversion from analog to digital data format. In consequence, there is an expense factor associated with hard modulation and cost tradeoff is usually encountered.

OTHER PHYSICAL FACTORS

Other solutions to EMC difficulties lie in the physical layout of equipments and subsystems within the aircraft. Each equipment processing at high power levels can be presumed to have a certain zone about the equipment or its associated external cabling, which is lethal in the sense of hazards to victim devices including their associated external cabling. The existence of this zone is

due to coupling influences of one form or another as described earlier. The spacing between equipment casing and wiring of potential source and victim devices must be kept as wide as possible within the limits of the aircraft.

An area in which this is particularly important is in the siting of antennas used for radar and communications subsystems. Interference can often be greatly reduced by locating the communications and radar antennas in entirely different portions of the aircraft.

PREDICTION AND ANALYSIS

GENERAL REQUIREMENTS

One of the primary uses of quantitative techniques of systems engineering for electromagnetic compatibility in naval aircraft weapon systems is in analyzing and predicting the interference among system elements. Unless accurate and applicable interference predictions can be made regarding the performance of systems, planning, installation, and operation may suffer from either wasteful expense of over engineering or the inadequacy of under engineering.

The goal of prediction and analysis within naval weapon systems is the development of analysis and prediction techniques capable of broad use with various weapon systems, communications, and radars with a wide variety of configurations.

The basic activities of EMC prediction and analysis involve the integration of existing knowledge and state-of-the-art analytical techniques into an efficient quantitative process. This process, to be effective, must be applicabile to the direct support of communications, radar, navigation, aircraft-function and controls, and all attendant planning operations in support of these functions.

The three most fundamental dimensions of prediction and analysis are time, distance, and frequency. For example, in communications and radar detection the basic problem is one of discriminating a desired signal from a noisy environment, where noise is defined broadly to include all feasible types of interference. Discrimination against these noises in favor of the desired signal can be made on the basis of time, distance, or frequency parameters.

The frequency parameter requires consideration of receiving system selectivity about each receiver response and the bandwidth of each transmitter emission, the spectral nature of transmitter outputs and receiver responses. Most prediction and analysis models are based on the frequency domain aspects of the problem.

If the interference is to occur, the signal and the interference must be present simultaneously. Situations that indicate heavy interference in one instance may in similar cases show only light interference if time-sharing plan is put into effect. For example, consideration must be given to the effects of rotating and scanning antennas and the effects of moving objects, as well as the percent of time when useful communication is an absolute necessity.

Distance or the length of propagation paths within the aircraft system is the third variable. Signal strength is a variable closely related to the distance variable. In many cases, signal strength may be considered an equivalent variable. Within an aircraft system itself, applicable distances lie within the near-field region, and this factor currently presents an unusually challenging problem to interference prediction analysts. Several preliminary solutions to the problem estimating near field effects have been developed, and are being evaluated at the Prediction and Analysis Branch, Naval Air Test Center, Patuxent River, Maryland.

The three basic variables of frequency, distance, and time, therefore, are the bases for the interference prediction analysis. Generally, all of the input functions used in the analysis prediction models are defined in terms of frequency as an independent variable and amplitude as a dependent variable. The latter is equivalent to the distance or signal strength variable in certain cases. Each of these input functions is defined statistically, and the statistical functions are classified according to their time dependence or time independence.

THE PREDICTION MODEL INPUT FUNCTIONS

The basic input functions required for describing the analysis and prediction model include:

1. The source function. This includes the output power levels of possible interference from potential interference sources and transmitters.
2. The transmission function. This includes the losses or the gains encountered by potentially interfering signals during transmission.
3. The susceptibility function, which defines the overall susceptibility to interference of the potential victim or receiving device.

After these three effective functions have been combined, an effective interference level can be determined. This level is defined as the "interference margin" (I), and is computed from the following relationship:

$$I = P_t - T - P_r \qquad (10\text{-}36)$$

The functions, expressed in decibels, are as follows:

I = interference margin

P_t = the effective power from the transmitter

T = the transmission loss or gain

P_r = power level required to interfere with the receiving device

An interference margin of zero decibels is defined to represent a marginal area between the interference and no-interference cases. A positive interference margin indicates an interference situation, and a negative interference level represents no interference.

TABLE 10-3 MATHEMATICAL MODELS FOR PREDICTION AND ANALYSIS

FUNCTION AND SIGNAL CATEGORY	MATHEMATICAL MODEL		
	Median Amplitude	Frequency	Standard Deviation
I. Transmitters:			
1. Fundamental	P_o^t	f_o^t	σ_o^t
2. Modulation Envelopes	$P_o - V^t \log\left[1 + K^t\left(\frac{\Delta f}{f_o^t}\right)^2\right]$	$\frac{\Delta f}{f_o^t}$	
3. Fundamental Harmonics	$A \log \frac{f}{f_o^t} + B$	nf_o^t	σ_n^t
4. Master Oscillator Harmonics	Same form as above	$n'f_{mo}$	σ_{mo}^t
5. Nonharmonically Related Spurious Emissions	Same form as above	f_{sp}^t	σ_{sp}^t
6. Intermodulation Emissions	Same form as above	$\lvert n_1 f_1^t \pm \dots n_j f_j^t \rvert$	σ_{it}^t
II. Receivers:			
1. Co-channel Response	$\begin{bmatrix} \text{Sensitivity} & S_o \\ \text{Interf.-to-Noise} & I/N \end{bmatrix}$	f_o^r	σ_o^r
2. Adjacent Channel	$S_o + I/N + V \log\left[1 + K\left(\frac{\Delta f}{f_o^r}\right)^2\right]$	$\frac{\Delta f}{f_o^r}$	σ_a^r
3. Out-of-band		$\frac{\lvert pf_{LO} \pm f_{IF} \rvert}{q}$	σ_{sp}^r
a. Spurious Responses	$S_o + I \log \frac{f}{f_o^r} + J$		
b. Intermodulation Responses	$m_1 P_1 + m_2 P_2 + \dots m_j P_j \geq S_o - C_{m_1, m_2, \dots m_j}$	$\lvert m_1 f_1^t \pm m_2 f_2^t \pm \dots \pm m_j f_j^t \rvert$	σ_{ir}^r
c. Other out-of-band	$S_o + D \log \frac{f}{f_o^r} + E$	All out-of-band	σ_{ob}^r
III. Propagation:			
1. Free Space	20 log f + 20 log d + 37	f	σ_{fs}^p
2. Surface Wave	E log F + K log d + F	f	σ_s^p
3. Skywave	Same	Same	Same
IV. Antennas:			
1. Main Beam	$Y_o - \left(G_m \log \frac{f}{f_o} + H_m\right)$	$\frac{f}{f_o^A}$	σ_m^A
2. Major Side Lobes	$Y_o - \left(G_s \log \frac{f}{f_o} + H_s\right)$	$\frac{f}{f_o^A}$	σ_s^A
3. Side and Back Lobes	$Y_o - \left(G_{sb} \log \frac{f}{f_o} + H_{sb}\right)$	$\frac{f}{f_o^A}$	σ_{sb}^A

Table 10-3 summarizes mathematical models used for prediction and analysis.

During the analysis, average values of parameters may be used or largest values for a worst-case analysis may be used. However, a better approach is to use statistical techniques. From various field measurements, or from a data bank, an estimate of the source power level P_t can be made, where this level is not exceeded by some safe percentage of time, such as 90 percent. Typically, a 90 percent interference power level is used, implying that the interference level is exceeded less than 10 percent of the time. Although the 90 percent level is used in most analyses, any one point (such as the 50 percent point) of a distribution, providing the distribution and the standard deviation are known, would suffice. The reason that a 90 percent point is chosen is that it suffices, in the total process, to a high assurance of predicting the interference no-interference case quite well. For example, if five normally distributed statistical numbers are added together and if it is 90 percent probable that each of them is not exceeded, then it is 99.85 percent probable that their sum is not exceeded. This is particularly significant in the discussion of the rapid cull method in the section on "Modulation Hardening." If a probability level of 50 percent is used, an appropriate adjustment must then be made in the confidence with which a particular interference case may be eliminated on the basis of the rapid cull alone.

Source Functions

An example of the 90 percent power level for a particular type of transmitting equipment is shown in Figure 10-36. In this figure the power level below the

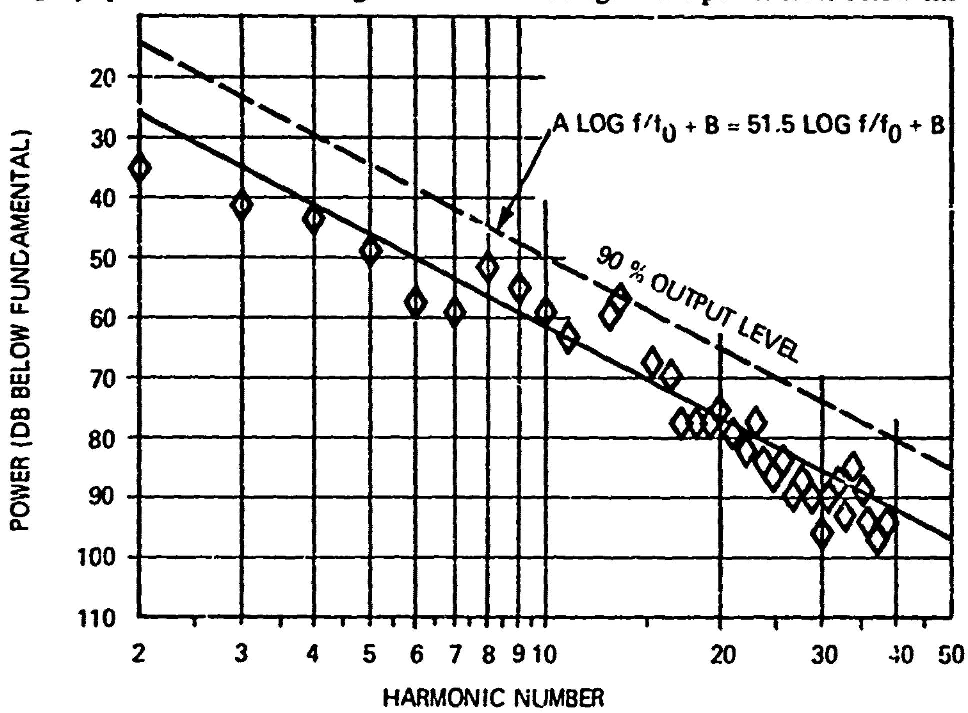


FIGURE 10-36 TYPICAL OUTPUT POWER LEVEL NOT EXCEEDED BY INTERFERENCE 90 PERCENT OF THE TIME

fundamental frequency is plotted versus harmonic number. The solid line is a least-square fit of the average value at each harmonic from numerous measurements made on a number of equipments for the same nomenclature. The data are normally distributed for the standard deviation of 10 dB. Since, for normally distributed data, a 90 percent level equals approximately 1.3 times a standard deviation, a line 13 dB above the average will give a good estimate of the 90 percent level. The straight line equation showing the relationship between output and frequency for this transmitter has the general form

$$P_t = A \log \frac{f}{fo} + B \tag{10-37}$$

where:

P_t = output power level in dB for interference source function

A = slope of source function for normalized frequency

B = intercept of source functions

f_o = fundamental or midband source output frequency

f = frequency under consideration

For the initial interference prediction step or rapid culling, this linear relationship between transmitter power output expressed in dBs and the logarithm of frequency has been shown to be the most efficient approximation to the transmitter output function. This equation can only be used for the source or transmitter function in interference prediction when appropriate data are available. While the 90 percent level can be determined as above, other levels can be determined for a normal distribution with the following basic relationships:

No.*	Percent
1.0	84
1.3	90
1.64	95
2.0	97.7
2.5	99.4
2.58	99.5
3.0	99.8

*Number of standard deviations (σ)

Transmission Function

The transmission function is evaluated as follows:

$$T = L_s + L_p - G_r - G_t \tag{10-38}$$

where:

T = transmission function, in dB

L_s = loss attributed to shielding, in dB

L_p = loss attributed to space propagation, in dB

G_r = antenna gain of receiving antenna, in dB (in direction of EMI source)

G_t = antenna gain of transmitting antenna, in dB (in direction of victim receiver)

When interference is transmitted by means of an interconnecting cable to the receptive device, the basic loss is a function of cable length and can be determined from the expression:

$$L(\text{cable}) = C + D \log d + E \log f \tag{10-39}$$

where:

$L(\text{cable})$ = loss in dB due to transmission via a conducting cable

C = intercept for cable propagation loss factor

D = slope of cable loss factor relative to distance

d = distance used by the unwanted signal through cable

E = slope of cable propagation loss factor in frequency

f = frequency

The general formula for space loss would have a similar form for propagation through environment space.

$$L(\text{space}) = F \log f + G \log d + H \tag{10-40}$$

where:

$L(\text{space})$ = loss attributed to space propagation, in dB

f = frequency of interfering signal propagated through space

d = distance between interfering source and victim receptive device

F = slope of propagation loss in frequency

G = slope of propagation loss in distance

H = intercept of propagation loss function

A more familar expression for free-space loss would be:

$$L(\text{space}) = 20 \log f + 20 \log d + 37 \tag{10-41}$$

where:

L = space loss, in dB

f = frequency, in MHz

d = distance, in miles

Another factor that may be included in the transmission function is the antenna gain factor. A simple formula for the antenna function is:

$$G = Y_o - K \log \frac{f}{f_o} + M \tag{10-42}$$

where:

G = antenna gain function

Y_o = main lobe gain of antenna

K = slope of antenna factor with frequency

M = intercept of antenna factor with frequency

f_o = main frequency of device for which antenna is used

f = frequency of potentially interfering signal.

Susceptibility Function

The susceptibility function, which shows the level of input power necessary

to produce interference in the receptive device, is expressed according to the following relationship

$$P_r = S_o + K \log \frac{f}{f_o} + J \tag{10-43}$$

where:

P_r = the power required to interfere with the receiver

S_o = minimum detectable signal level in receptive device

K = slope of susceptibility function with frequency

J = intercept of susceptibility function

f_o = center of frequency, or tuned frequency, of receptive device

f = frequency of interest

INTERFERENCE PREDICTION METHODOLOGY

As stated earlier, the interference margin depends upon the three basic interference prediction functions (source, transmission, and susceptibility). These are known as the input functions and are expressed in the following equation:

$$P_t - T - P_r \geq 0 \tag{10-44}$$

Another way of depicting schematically the application of the various input functions in the interference prediction process is indicated in Figure 10-37. In this diagram, the interference margin indicated is that resulting from the application of the source function to the transmission function, subsequently related to the susceptibility function. If this relationship is greater than or equal to zero, interference is likely.

As pointed out earlier, the 90 percent levels for all these functions are used in the initial or rapid cull. This is done to quickly eliminate obvious cases of non-interference. Prediction itself is a two-step procedure involving what is known as a rapid cull and a frequency cull. These procedures have been developed and refined by the Electromagnetic Compatibility Analysis Center (ECAC), Rome Air Development Center (RADC), and other commercial and government agencies and offices. Figure 10-38 provides an overall view of the steps in analysis and prediction, including the input functions, and the rapid cull and frequency cull steps.

Rapid Cull

In the first of these steps, to locate areas in which interference is likely to

SOURCE FUNCTION (P_T)

1. INTENDED RADIATION
2. HARMONICS OF INTENDED RADIATION
3. HARMONICS OF MASTER OSCILLATOR AND LOCAL OSCILLATOR
4. NON-HARMONICALLY RELATED SPURIOUS
5. SWITCHING IMPULSES ON POWER LINES
6. IGNITION NOISE
7. NATURAL NOISE
8. ARC WELDING NOISE
9. BRUSH-TYPE MOTOR NOISE
10. NOISE-FROM INDUSTRIAL, SCIENTIFIC MEDICAL SOURCES

TRANSMISSION FUNCTION (T)

1. NEAR FIELDS
2. FAR FIELDS
3. INDUCTIVE COUPLING
4. CAPACITIVE COUPLING
5. RESISTIVE COUPLING
6. CABLE LOSS
7. ANTENNA EFFECTS
8. SHIELDING EFFECTS
9. EXTERNAL FILTERING EFFECTS

INTERFERENCE MARGIN (I)

COMPARISON BETWEEN INTERFERING ENERGY AVAILABLE AND ENERGY REQUIRED TO CAUSE INTERFERENCE

SUSEPTABILITY FUNCTION (P_R)

1. ENERGY ENTERING ANTENNA TERMINALS
2. ENERGY ENTERING INTERCONNECTING SIGNAL LEADS
3. ENERGY ENTERING DIRECTLY THROUGH CASE SHIELDING

FIGURE 10-37 INPUT FUNCTIONS AND THEIR APPLICATIONS TO THE INTERFERENCE PREDICTION PROCESS

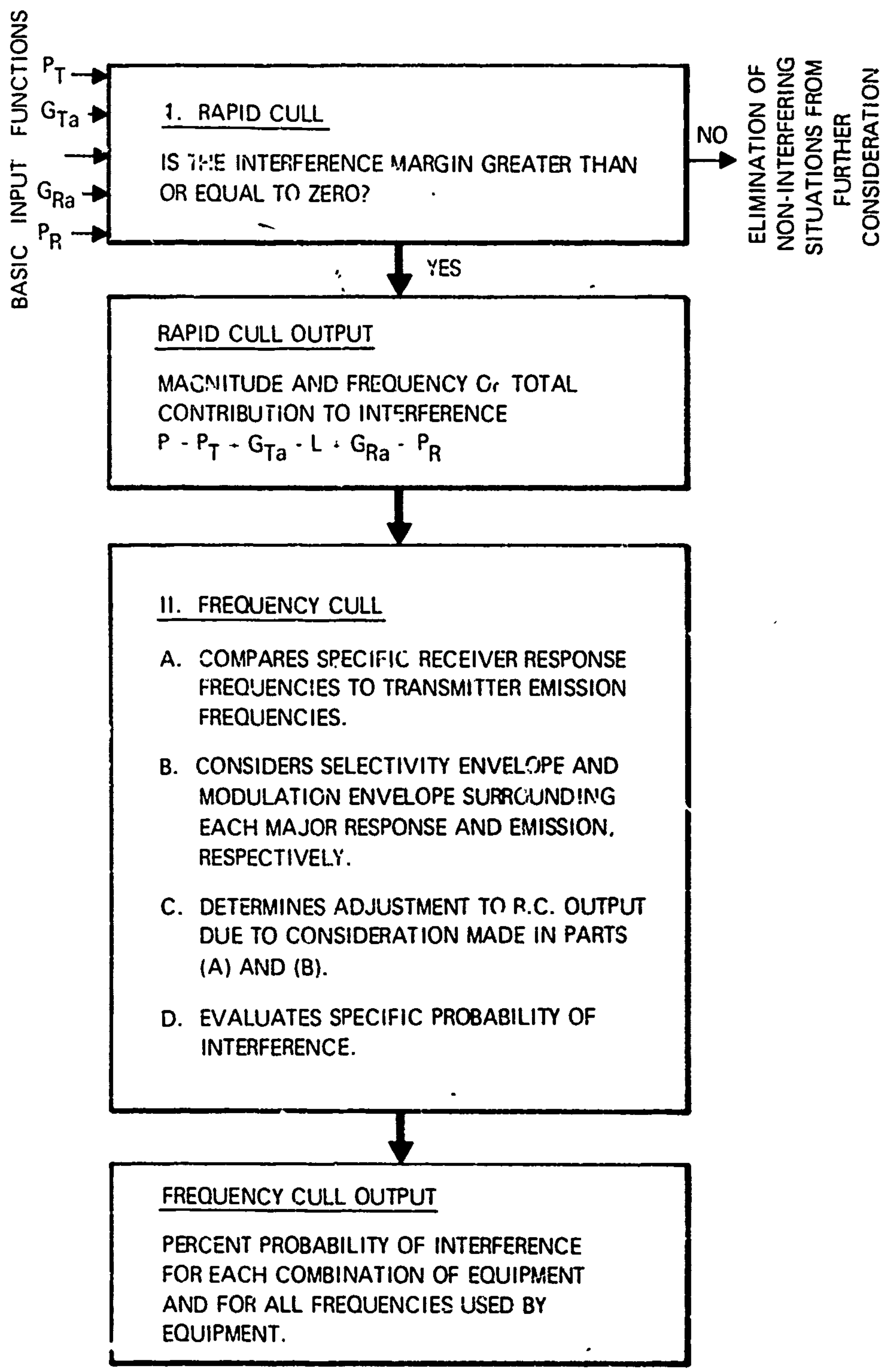


FIGURE 10-38 BASIC TWO-STEP PROCESS FOR INTERFERENCE PREDICTION

occur, the rapid cull or search is made. This culling step identifies outputs that:

1. Are unlikely to cause interference
2. May cause interference
3. May interfere even under most favorable conditions

This first culling step or rapid cull consists merely of continuously comparing the amplitudes of transmitter emissions and receiver spurious responses, rather than considering the discrete spectra associated with each element. The purpose of the amplitude cull is to eliminate obvious cases of noninterference from the analysis. This greatly reduces the number of cases that must later be subjected to detailed analysis. The rapid cull does not use the fact that emissions that are near spurious response frequencies may not cause interference. The result is a worst-case estimate of interference. For example, if a 90 percent probability is selected for the interference prediction, the interference margin becomes the statistical sum of the three functions and corresponds to about 99 percent. This means that 99 percent of the time interference will not exceed the established level. The results of the rapid cull will eliminate all frequency ranges in which the interference margin is less than zero.

Frequency Cull

After the rapid cull removes all noninterference cases, the second selection or frequency cull is made. Frequency culling consists of comparing all transmitter output frequencies with all receiver spurious response frequencies within the range of possible interference, as determined by the rapid cull. In this procedure, parameters such as modulation bandwidth, emission type, and IF bandwidth are used to determine if the emission is within the spurious response bandwidth of the receiver. This separation between each pair of frequencies compared must be correlated with a composite of the bandwidth of the receiver and the bandwidth of the transmitted signal. This will yield an amplitude correction factor for the interference module, as determined in the rapid cull.

In general, three frequency ranges will be included in the frequency cull analysis, including:

1. The region above both the transmitter and the receiver fundamental frequencies
2. The region between the fundamentals
3. The region below both fundamentals

The result of the operations performed in the frequency cull is an estimate of the interference margin, that is, the amount by which the left number of equation 10-44 exceeds zero. The interference margin M is given by

$$M = P_t - P_r + G_t - C_r - L \qquad (10\text{-}45)$$

where:

G_t and G_r are the respective antenna gains

C_r is the coupling function

L is the propagation path loss

Thus, the rapid cull provides the initial upper estimate of M and the frequency cull decreases M by as much as the other factors considered in the frequency cull will allow.

The process known as the frequency cull results in the translation of an answer from decibels to the probability of interference for each source at specified discrete frequencies.

To put the interference margin into its proper form, the statistical nature of each variable must be considered. A typical graphical measure that may be used to translate the interference margin into the probability of interference is shown in Figure 10-39. The lower marked with TFIL = RFIL is used when the interference margin has arisen from interference caused at or near the tuned frequency of the receiver by the fundamental output transmitter. The curve marked

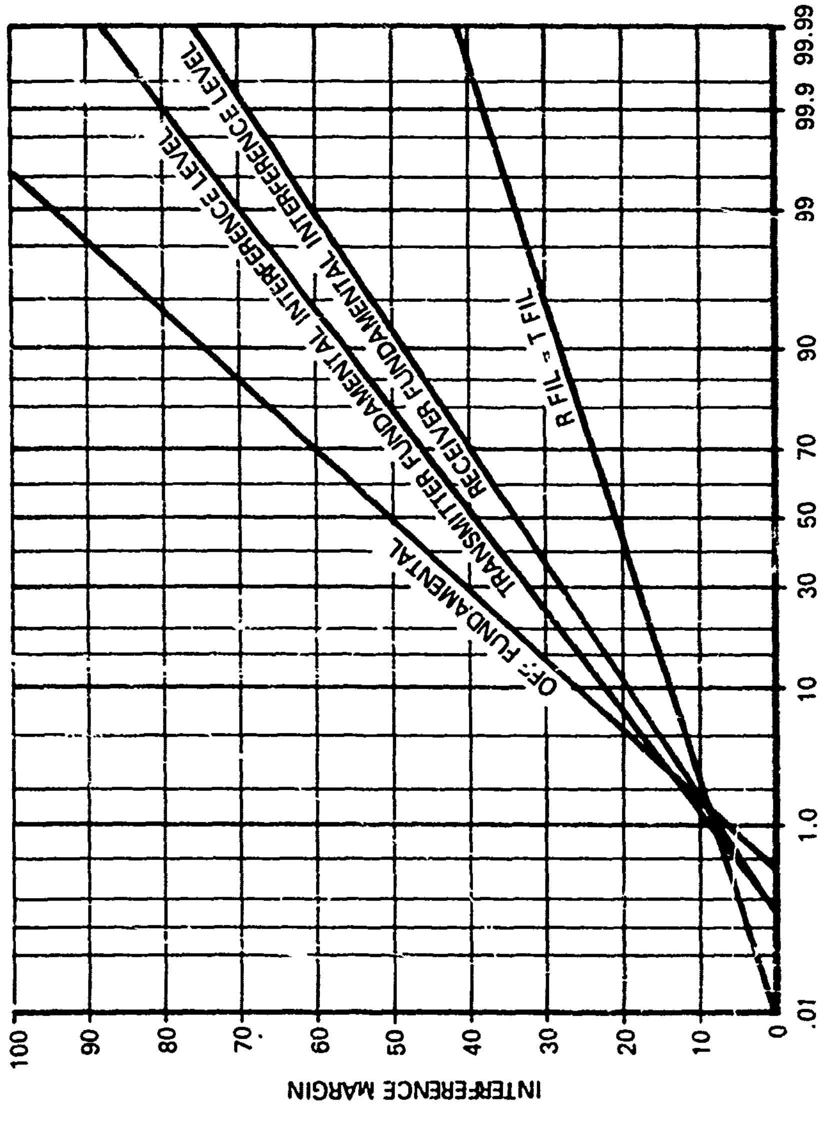


FIGURE 10-39 TYPICAL RELATIONS BETWEEN INTERFERENCE MARGIN AND PROBABILITY OF INTERFERENCE

"RFIL" is used when interference from any source enters a receiver at or near its tuned frequency. The "TFIL" curve is used when interference is caused by the fundamental output of the transmitter. The "off fundamental" curve is used when neither the receiver response nor the interfering emission is at the tuned frequency of the respective device.

As indicated by the curves of Figure 10-39, there is a wide difference in the spread of the statistical distributions depending upon whether or not both fundamentals, one fundamental, or no fundamentals are involved in the particular situation under investigation. The wider spread of the statistical distributions at other than design frequencies reflects the fact that the uncertainties are small at the design frequencies and are large at frequencies other than the design or tuned frequencies.

AUTOMATIC DATA PROCESSING

The entire analysis procedure can be implemented through both manual and automatic data processing measures. However, due to the statistical nature of the interference problem, the manual computation of interference probabilities and margins is tedious and sometimes impossible. Hence, standardized functional statistical forms for all of the input functions have been established and high speed digital computer processes have been developed and programmed.

This high speed computation process accepts the established statistical forms and computes the detailed probabilities of interference, both on the rapid cull and the frequency cull. The only difference between a manual and the machine automated methods is the speed of the prediction. As pointed out earlier, the principal work in this area has been performed by the EDAC and RADC. For predicting EMC environments, the limitations on existing automated ADP prediction and analysis programs are as follows:

1. Are not based on naval aircraft electromagnetic scenarios
2. Do not consider the nonfunctional sources in a naval aircraft such as control voltages, digital communications, aircraft controls, and fire controls
3. Do not include the types of coupling phenomena normally associated with the EMI within naval aircraft such as cable coupling, ground circuits, and high-power effects
4. Do not include types of non-communications equipments that may be susceptible to the physical proximity of high power electromagnetic effects

The Naval Air Systems Command, assisted by the facilities and personnel of the Naval Air Test Center, Patuxent River, Maryland, is working actively in this area to develop and to extend the knowledge and the capabilities in predicting and analyzing EMC in naval aircraft systems. Efforts will basically be extensions and refinements of basic models provided by EDAC and RADC, specifically tailored to naval air weapon systems. Addendum 10-A gives a brief description of existing analysis and prediction computer programs that are adaptable to analysis and prediction of EMC in naval air weapon systems.

TEST AND VALIDATION

GENERAL

The test and validation phase of EMC systems design is directed toward experimental evaluation of subsystems and component devices to determine whether or not an EMC hazard exists or is likely to exist.

There are two philosophical approaches to the test and validation of systems, subsystems, and components. The first of these is predicated on the basis of laboratory measurements, while the second involves the use of "on site" data. The laboratory measurements philosophy is predicated on the assumption that data taken in a controlled environment can indicate performance in the aircraft, while on-site philosophy avoids this assumption, and testing is accomplished on the complete system in the actual environment encountered in use. Each of the philosophies has advantages and disadvantages.

In laboratory testing, the system and subsystem components are tested in a controlled environment to determine radiation and susceptibility. The environment in which testing has been done has traditionally been a shielded chamber.

One of the chief advantages of shielded chamber testing is the absence of extraneous atmospheric and manmade noise from the measurement environment. Methodologies have been compiled for tests in both reflective and anechoic chambers; however, construction of the latter for frequencies below the UHF range is not generally practicable. In either case, the test methods involve either measuring in a calibrated manner equipment emission spectra or the effect of known RF interference levels upon the equipment. Measurements typically include three types of emission and susceptibility:

1. Radiated electric
2. Radiated magnetic
3. Conducted (signal and power line)

Measurements can be performed on individual equipments or on groups of equipments in a system. When tests on individual equipments are performed, it is important that all load conditions be maintained at those levels comprising what is regarded as normal operation, except that the equipment is operated in the limiting circumstance that produces worst case radiation or susceptibility. The purpose of this is to insure that test results will represent the normal operational state of the equipment. The tests should be comprehensive and include all operating modes.

Tests of systems equipments are particularly applicable where an assessment of the consequences of interference is desired. Whenever system testing is conducted, all applicable configurations should be considered.

With the development of larger shielded chambers, it has become possible to test an entire avionics system installed in an aircraft under controlled laboratory conditions. The advantages of such testing are obvious: it becomes possible to duplicate actual operating conditions with a degree of realism not possible in testing individual component equipments.

The disadvantages of laboratory testing are that particularly in the case of reflective wall shielded chambers, it is difficult to obtain data that are not contaminated by such variables as multipath reflection, coupling to the walls, and standing waves. Moreover, in such an environment the data are strongly a function of equipment placement, shape, and size of the room, and a variety of other extraneous variables.

As applied to NAVAIR systems, "on site" testing involves actual flight testing of the aircraft with the avionics systems installed and operating. In this type of test the main effort is directed toward evaluation of actual incompatibilities encountered rather than measurements of signal levels. The primary advantage of flight testing is realism in the absolute. The disadvantages include cost, especially if testing is long, since both pilots and test personnel must be available and aircraft fuel provided. Moreover, where unsuspected incompatibilities exist, there is a very real possibility that the aircraft will crash, resulting in loss of equipment and personnel. The result of the testing phase is an acceptance-rejection decision. Implicit in the decision are factors such as the cost of retrofit fixes and the possibility of waivers, that is, achievement of compatibility by altering the mission profile.

TEST PROCEDURES

The test procedures involved in NAVAIR validation evaluations are included in several EMC specifications and standards. Each of these standards includes particular requirements of test equipment and methodology. The purpose of the specifications and standards is to achieve uniformity in measurement methods and results.

The currently effective specifications and standards are listed below:

Number	Title	Preparing Activity
MIL-STD-220	Method of Filter Loss Measurement	Army (EL)
MIL-STD-449D	Radio Frequency Characteristics, Measurement of	Navy (EC)
MIL-STD-461A	EMI Characteristics, Requirements for Equipment	Navy (EC)
MIL-STD-462	EMI Characteristics, Measurement of	Air Force (11)
MIL-STD-463	Definitions and System of Units, EMI Technology	Army (EL)
MIL-STD-469	Radar Engineering Design Requirements	Navy (SH)

MIL-B-5087	Bonding Electrical and Lightning Protection for Aerospace Systems	Air Force (11)
MIL-E-6051D	EMC Requirements for Systems	Air Force (11)
MIL-STD-285	Attenuation Measurements for Enclosure, Electromagnetic Shielding for Electronic Test Purposes, Measurement of	Army (EL)
MIL-STD-1310(SH)	Shipboard Bonding and Grounding Methods for EMC	Navy (SH)

The basic instrumentation required for measurements under provisions of the above documents includes such items as calibrated RFI receivers, antennas, current probes, noise generators, and power oscillators covering frequencies from near DC to above 1 GHz.

Emission test procedures are directed toward developing plots of electric (E) and magnetic (H) field and conducted emissions as a function of frequency. Calibration is by use of substitution sources.

E and H fields are measured at a standard distance, usually three feet from the equipment, using various types of antennas depending on frequency and type of field. The forms of magnetic field antennas generally used are circular loops. Electric field antennas include vertical rods, dipoles, and as shorter wavelengths are reached, log periodics, log spirals, and horns. Calibration is achieved by use of a substitution source, usually at the receiver input, the data being converted to appropriate units by antenna factors.

Conducted emission measurements are made by use of current probes or line impedance stabilization networks. Both devices permit extraction of signals from signal or power lines through a known transfer characteristic. This in turn allows computation of calibrated results.

Susceptibility testing involves the injection of known signals and noise into power and/or signal lines while the performance of the equipment is evaluated. When the signal is injected through an abnormal route such as the power line of an amplifier, measurements of the amount of signal appearing at the output are made. When the signal is injected at the normal input, measurements of spurious responses, harmonics, and intermodulation are made.

Another form of susceptibility testing involves subjecting the equipment to known electromagnetic fields derived from CW or noise sources. Measurements in this case are of the amount of coupled signal at the output or are expressed in terms of degradation such as bit error rate.

The acceptance rejection criteria specified in the standards are usually expressed in the case of emissions in the form of fixed radiation or conduction

limits expressed as a function of frequency. The limits place a maximum value on permissible radiation or conduction. In the case of susceptibility testing, acceptance criteria are expressed in a variety of measures related to shield attenuation, spurious product levels, bit error rates, and other considerations.

TEST RESULTS

The results of a test under the applicable specification, while indicating the acceptability of a particular equipment, do not yield information sufficiently real to serve as the basis of an absolute decision as to whether the equipment is usable in a particular airborne system or subsystem. Often it is possible to incorporate an equipment that does not initially comply with a particular specification in the system if:

1. The equipment characteristics can be brought within tolerance by retrofit procedures
2. Even though the equipment does not comply with the standards, its interaction with other equipments is not degraded
3. Noninterfering operation is possible if constraints on the aircraft mission or operating scenario are made

Retrofit procedures involve the remedial implementation and application of EMC corrective measures to the offending equipment. A typical example of a retrofit procedure would be the design of a new housing for the equipment having greater RF integrity. Retrofit procedures are usually expensive and, where it involves shielding, may so encumber the equipment as to preclude its normal use or installation in the space provided in the aircraft. Some retrofit procedures are extremely simple however, such as the inclusion of an additional or modified power line filter.

When retrofit procedures are too costly or appear to have little chance of success, the equipment may be acceptable despite its lack of compliance. This can occur when the equipment does not create interference in its intended role or when the role of the equipment in the aircraft operation can be altered to prevent harmful interference.

In these circumstances, a waiver of the requirements may be issued and the equipment accepted. The decision underlying the waiver must include a variety of factors including mission objectives, costs, and development schedules.

DISCUSSION OF EMC CORRECTIVE MEASURES

OPERATIONAL CONSIDERATIONS

In airborne electronic, electromechanical, and electromagnetic systems and subsystems, it is often possible to reduce the extent of electromagnetic incompatibility by regulating the operating scenario. In particular, a determination of which systems and subsystems need be in simultaneous operation must be made. In general, this involves assignment of operating priorities.

Operating priorities will differ greatly, depending on the function and purpose of the airplane. For example, the relative importance of fire control radar in a reconnaissance aircraft differs from that in a fighter aircraft. For this reason, and because of equipment variations, operating priorities must be analyzed for a particular aircraft type and function rather than for all aircraft in general.

In assessing electromagnetic compatibility, consideration must be given to the extent to which a particular incompatible operating configuration is used, and consequences to the victim system of interference. The seriousness of the interference consequences plays a large role in determination of whether interference can be tolerated. For example, if interference causes a malfunction in the aircraft flight control system, it is probable that the aircraft will crash. Clearly, interference of this type, no matter how infrequent, cannot be tolerated. On the other hand, consider that a communications transmitter interferes with ASW detection equipment in an ASW aircraft. This type of interference does not endanger the aircraft or personnel but influences the ability of the aircraft to accomplish its mission. Another example of interference is the situation where radar pulses are present in the voice communications circuit. This type of interference may be merely an annoyance and does not necessarily constitute an EMC hazard. At another extreme, complete loss of articulation may result.

The above examples have illustrated that there are three levels of EMC hazard or risk:

1. Severe hazard – the consequences of the interference are loss of life, aircraft, or both.
2. Moderate hazard – the consequences of the interference are failure of mission-related equipment, leading to inability of aircraft to fulfill its intended purpose.
3. Minimum hazard – the consequences of the interference are mainly in the form of operator annoyance. The interference does not endanger the aircraft or the mission.

The amount of interference that can be tolerated depends on the category of the interference. Interference that creates severe hazard can clearly never be tolerated. Interference in the moderate hazard category can in certain circumstances be tolerated. Specifically, interference can be tolerated if the culprit and victim subsystems are not operating simultaneously. As an example, suppose the radio altimeter interferes seriously with search radar. It is not generally necessary to operate the radio altimeter continuously. This leads to the possibility that the radio altimeter can be secured during search radar operation, eliminating the consequences of the interference.

Scheduling of operations of incompatible systems and subsystems is one of the most useful means of achieving overall compatibility since it affords a highly economical method of alleviating difficulties otherwise not amendable to solution without extensive design or redesign. Whenever such scheduling is undertaken, it must be remembered that the overriding consideration is the aircraft mission and not compatibility. Scheduling is not a solution to an EMC problem if the scheduling itself interferes with the mission.

SUPPRESSION AND RETROFIT

The term "suppression and retrofit" refers to techniques that can be used in the reduction of interference from and incompatibility between existing equipments. Such techniques are more appropriately applied within an equipment during its design. The techniques are applicable both to interference sources and victims. The paragraphs below contain a brief discussion of suppression methods.

Shielding Principles, Materials, and Methods

Shielding is a basic method for the reduction of radiated signals by surrounding the radiating source with a closed conducting surface. The conducting material attenuates or reduces any radiated waves that try to pass through it. The amount of attenuation for any given material and frequency may be calculated or found in charts.

The simplest basic electromagnetic wave is the plane wave, also known as a TEM (transverse electromagnetic) wave. This wave is composed of an electric field and a magnetic field at right angles to each other and to the direction the wave is traveling. The geometry of a transverse electromagnetic wave is illustrated in Figure 10-40.

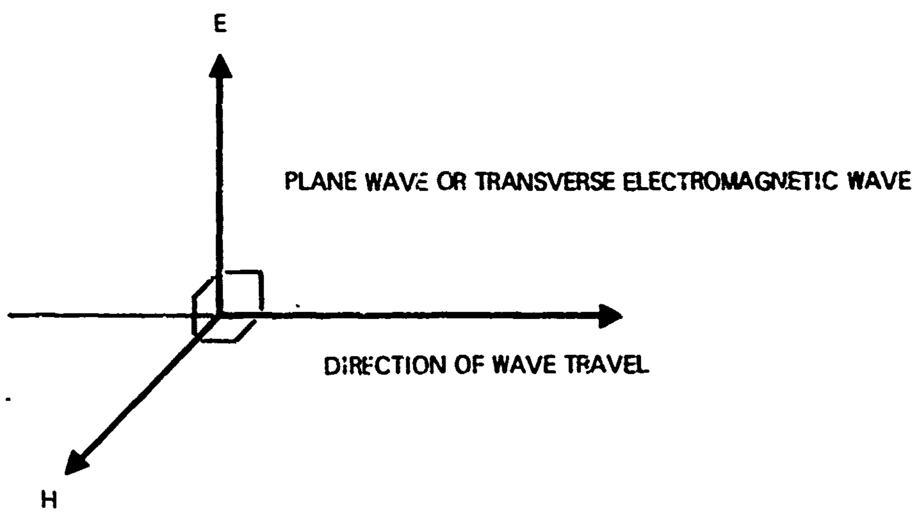


FIGURE 10-40 PLANE WAVE

The magnitude E and H field components in a wave are related to each other by the impedance of the medium in which the wave is traveling. Thus, the impedance is given by the relationship $Z = E/H$. In free space (air or vacuum), this impedance is 377 ohms.

For copper at one megacycle, the impedance is roughly .0004 ohm, which is very low compared with that of free space. If the wave encounters a boundary between two media such as air and copper, which exhibit a considerable mis-match in impedance, most of the wave is reflected, just as light waves reflect from a mirror. This is illustrated in Figure 10-41. However, a small part of the wave energy penetrates the metal and attempts to travel through it, but, since the conductivity of the metal is high, the wave is rapidly attenuated. The energy decrease due to reflection is called reflection loss, and that due to traveling through the metal is called absorption loss.

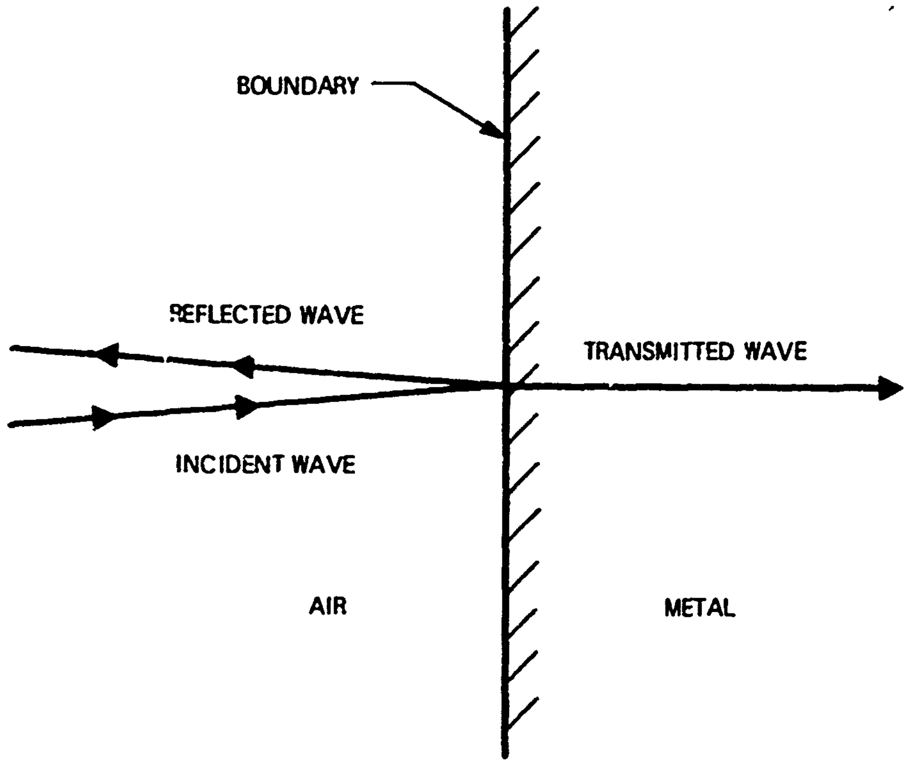


FIGURE 10-41 REFLECTION FROM A BOUNDARY

If the metal is a sheet with uniform thickness, the wave passing through the sheet meets a secondary boundary when it leaves the sheet. Thus, a second reflection occurs at this boundary, causing an additional loss. This situation is represented in Figure 10-42.

The total effectiveness of a sheet of shielding material is given by the formula:

$$S = A + R + B.$$

where:

A is the absorption loss

R is the reflection loss (both surfaces)

B is the loss due to multiple reflections within the shield

all expressed in dB. (See Figure 10-43 for nomographs.)

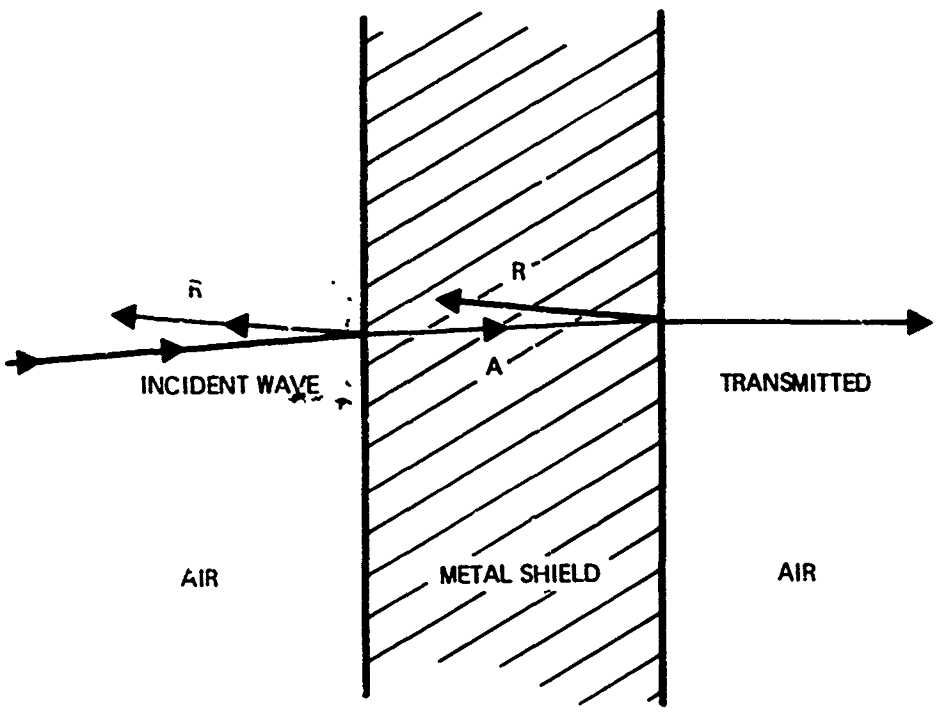


FIGURE 10-42 WAVE PASSING THROUGH A SHIELD

The absorption loss in the metal is higher for materials with low impedance, that is, good conductors such as copper. For a given thickness, it is proportional to frequency, that is, inversely proportional to wavelength in the material. Thus, it is difficult to obtain good shielding at low frequencies from realizable thicknesses of shield material. Materials with magnetic properties, such as iron, afford increased absorption loss at low frequency. Unfortunately, the conductivity of iron is less than desirable. This has led to the development of special shielding materials that are alloys of iron, copper, and other substances. These are used where shielding over a wide range of frequencies is desired. Special magnetic

shielding materials are available such as Permalloy, Mu-metal, and Conetic.

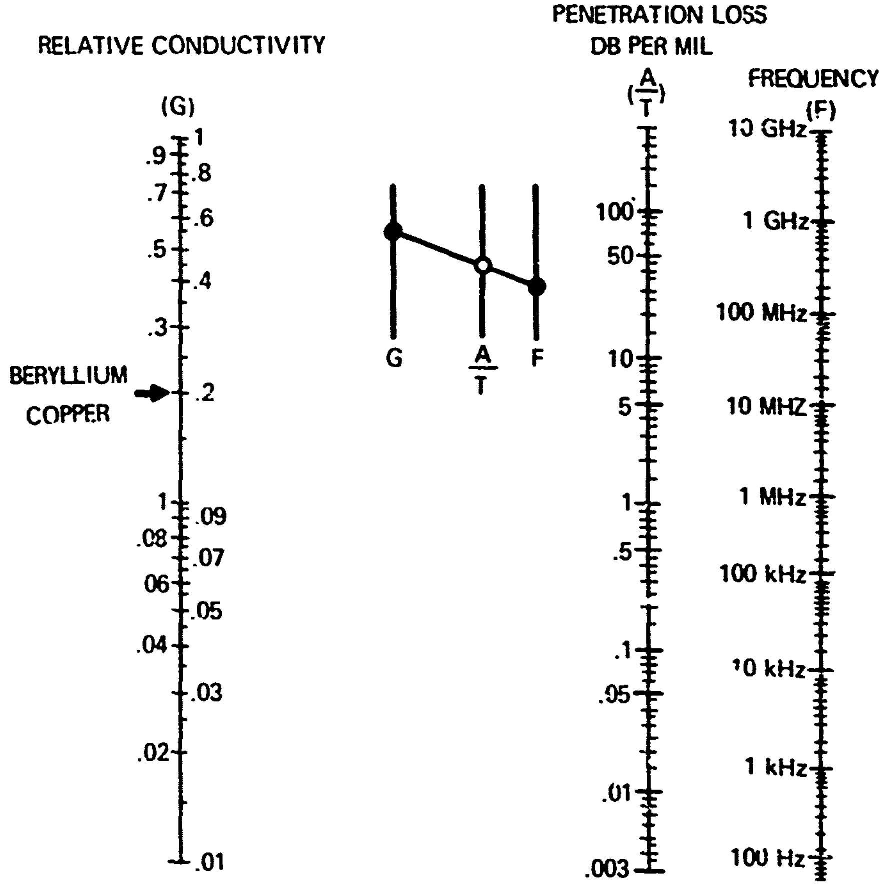
The impedance Z of any nonconductive medium may be found by the following formula:

$$Z = \sqrt{\frac{\mu}{\epsilon}} \qquad (10\text{-}46)$$

where:

μ is the magnetic permeability and

ϵ is the electric permitivity of the medium.

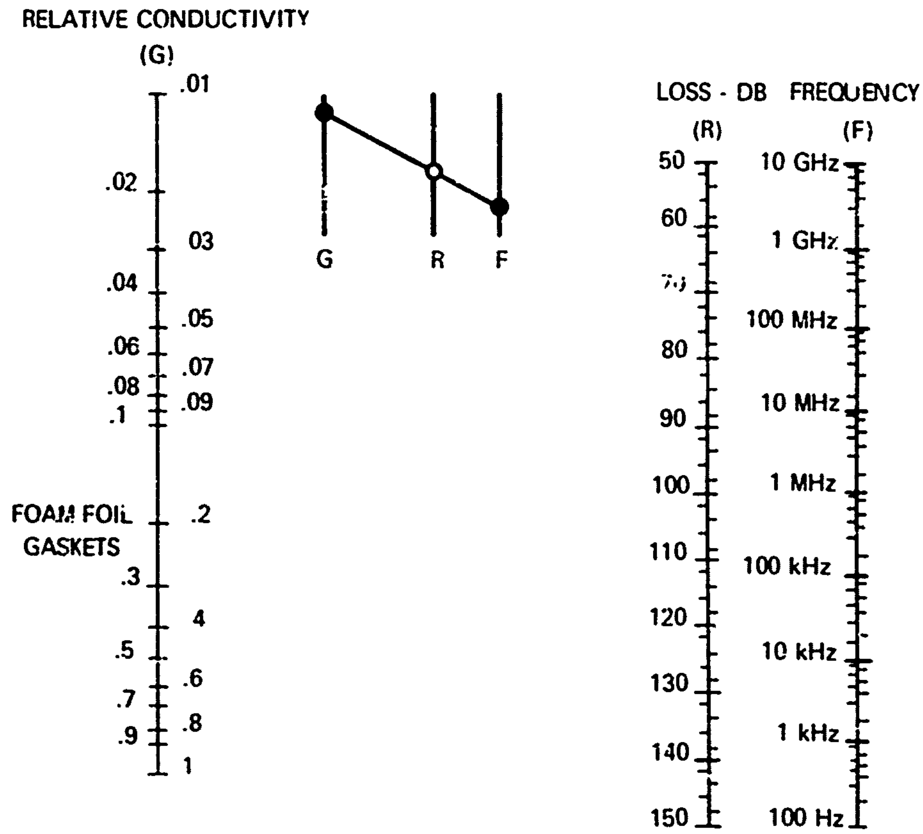


DETERMINATION OF THE ABSORPTION OR PENETRATION LOSS OF SOLID NONMAGNETIC MATERIALS. MULTIPLY FACTOR BY THREE.

FIGURE 10-43(a) NOMOGRAPH FOR A FACTOR. (MULTIPLY FACTOR BY 3)

Values for these may be found in tables. For free space (vacuum), the values given

$$Z = Z_o = \sqrt{\frac{\mu_o}{\epsilon_o}} = 376.7 \text{ ohms} \tag{10-47}$$



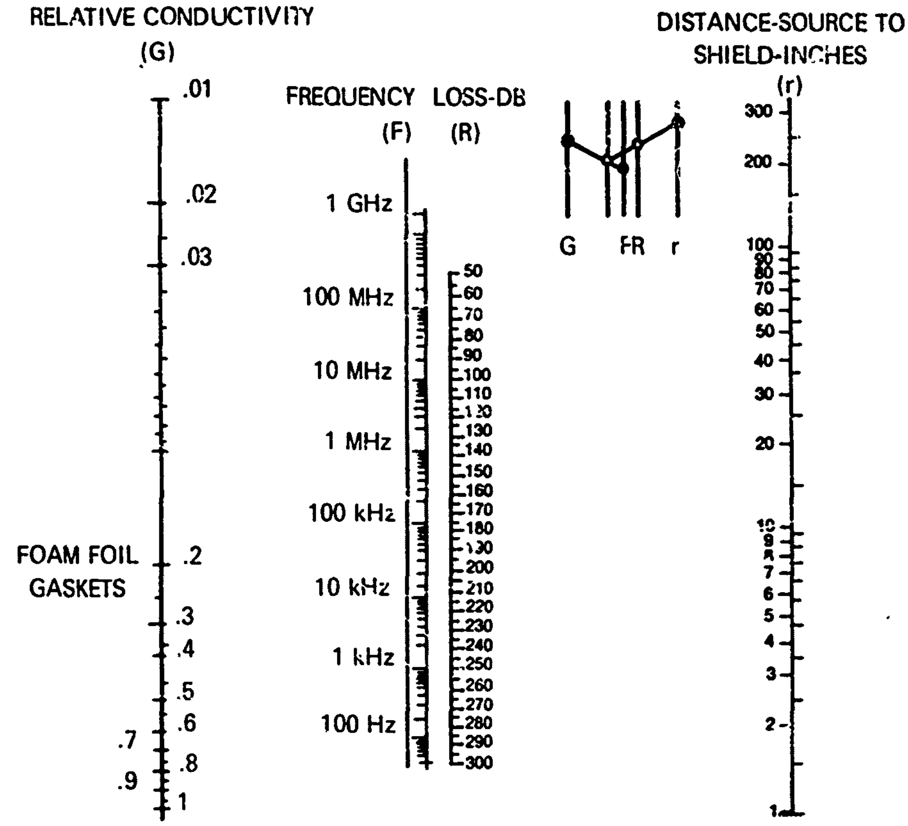
DETERMINATION OF THE REFLECTION LOSS OF PLANE WAVES FOR SOLID NONMAGNETIC MATERIALS.

FIGURE 10-43(b) NOMOGRAPH FOR R FACTOR

For any lossless dielectric material (including free space), E and H are in time phase, and Z is a pure resistance. For a good conductor such as copper, the impedance is given by the formula:

$$|Z| = \sqrt{\frac{\omega\mu}{\sigma}} = \sqrt{\frac{2\pi f\mu}{\sigma}} \tag{10-48}$$

Where $|Z|$ is the magnitude of the impedance, ω is $2\pi f$, f is frequency, μ is magnetic permeability and σ is conductivity.



DETERMINATION OF THE REFLECTION LOSS OF ELECTRICAL-FIELD WAVES FOR SOLID NONMAGNETIC MATERIALS.

FIGURE 10-43(c) NOMOGRAPH FOR B FACTOR

It is not practical to use solid shields on all equipments, since ventilation is necessary. Openings in a shield make it less effective, as signals can leak out. However, certain things can be done to minimize this leakage. For example, suppose a hole is drilled through a shield for ventilation or some other purpose. The hole then acts like a short waveguide, and lets some of the incident wave go through. If the hole is small enough and long enough for the highest frequency involved, it will reduce the signal considerably by acting like a waveguide below lowest mode cutoff frequency. It is general practice to place in such a hole, a metal tube at least three times as long as its diameter.

If several rectangular or hexagonal tubes are placed side by side to cover a large opening, the combination is called honeycomb. It is good for ventilation

openings and gives fairly constant attenuation below the cutoff frequency, which is about 24 GHz for 1/4 inch cells. A length-to-diameter ratio of three to one gives about 80 dB attenuation. Good metal-to-metal contact is needed around the edge of honeycomb.

Another approach is perforated screen. Metal sheets with many holes punched out are often used for shields where some ventilation is needed. Attenuation in such perforated screens is largely by reflection. The holes act as waveguides but are short compared with diameter, and therefore, are somewhat leaky, especially for magnetic fields below 1 MHz. Attenuation averages about 50 dB.

Woven copper or bronze wire screens similar in appearance to window screens are also used for shielding. Again, reflection gives most of the attenuation. Screens are poorer shields than perforated metals. However, they are sometimes used as shielding in front of indicator lamps or display devices, such as "Nixie" tubes.

Bonding

The term "bonding" refers to the electrical interconnection of the metal cabinets and chassis of equipments and accessories in a system. This reduces any voltages that might appear between the units.

Some general rules to follow for good bonding practice are listed below:

1. Equipment racks, cabinets, instruments and structural members of the aircraft should be properly bonded together and to the ground system
2. Metal-to-metal direct contact between bare, clean surfaces is desirable to insure low-impedance contact
3. Permanent type bonds, such as directly welded, solder-sweated, or brazed joints are preferable to bolted connections or connecting by bond straps
4. Round items such as a conduit should be bonded with suitable clamps or with bolt-on clamps with jumper straps
5. Bond straps should have a width of one-third the length or greater. Length should not exceed three inches, if at all possible
6. A soldered bond joint should be joined mechanically before soldering, by bolts, rivets, or sheet-metal screws
7. For bonds that are bolted or clamped, star-type lock washers are useful, since the sharp teeth can bite through surface corrosion to make good electrical connection. A graphic representation of electrical impedance of wire and strap bonds as a function of bonding geometry is shown in Figure 10-44(a)

Often, however, where equipment cabinet work is concerned, it is not possible to have permanent bonds of the type described above without making it impossible to service the equipment. This problem can be met by using removable panels to the edges of which are attached conductive gaskets or finger stock. In installations of this type, it is important that the contact between the gasket or finger stock be firm and even throughout, and that the material be free from

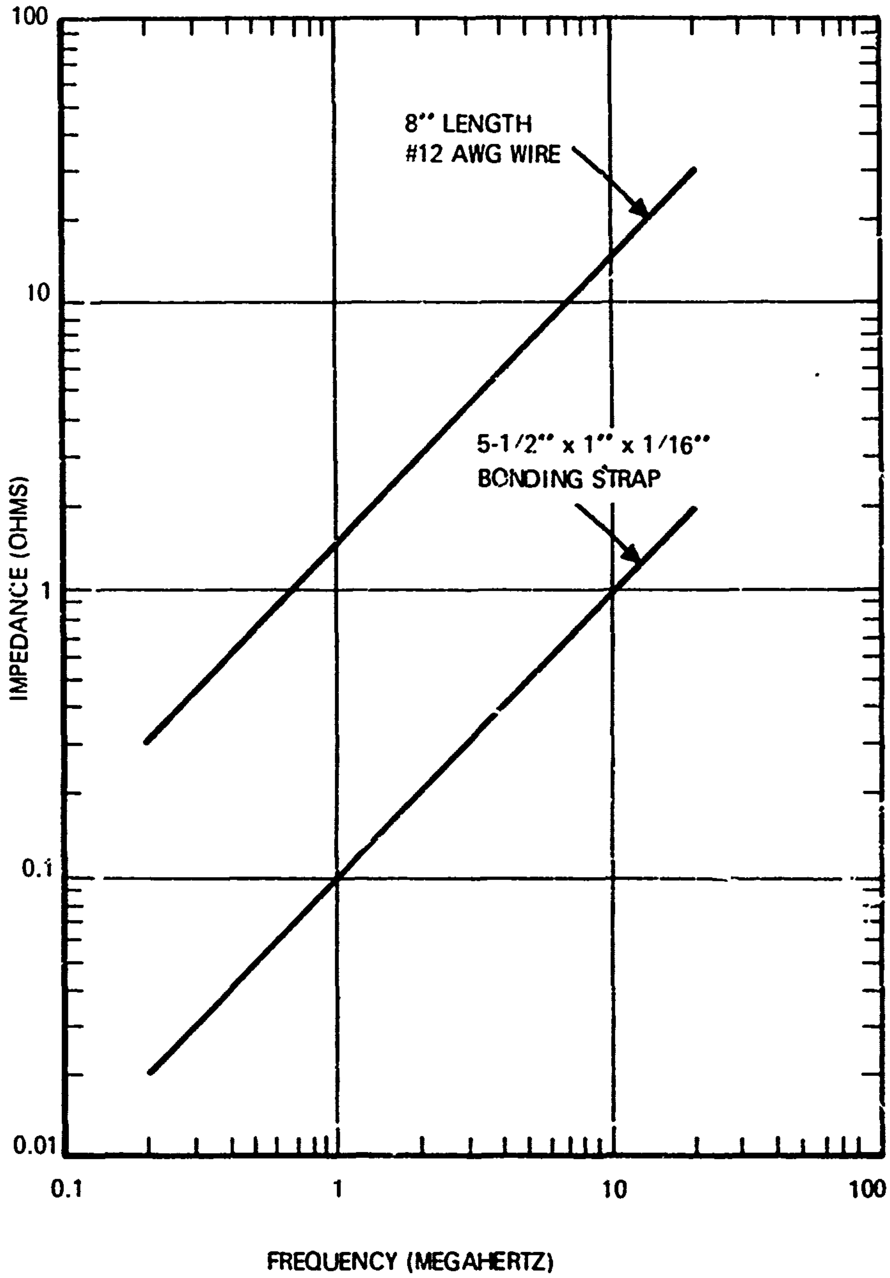


FIGURE 10-44(a) IMPEDANCE OF BOND STRAP VS NO. 12 AWG WIRE

foreign bodies and corrosion. Cracks resulting from improper sealing of the gasket material can act as slot antennas.

Figure 10-44(b) shows a type of "finger stock" serrated spring commonly used in bonding equipment housings.

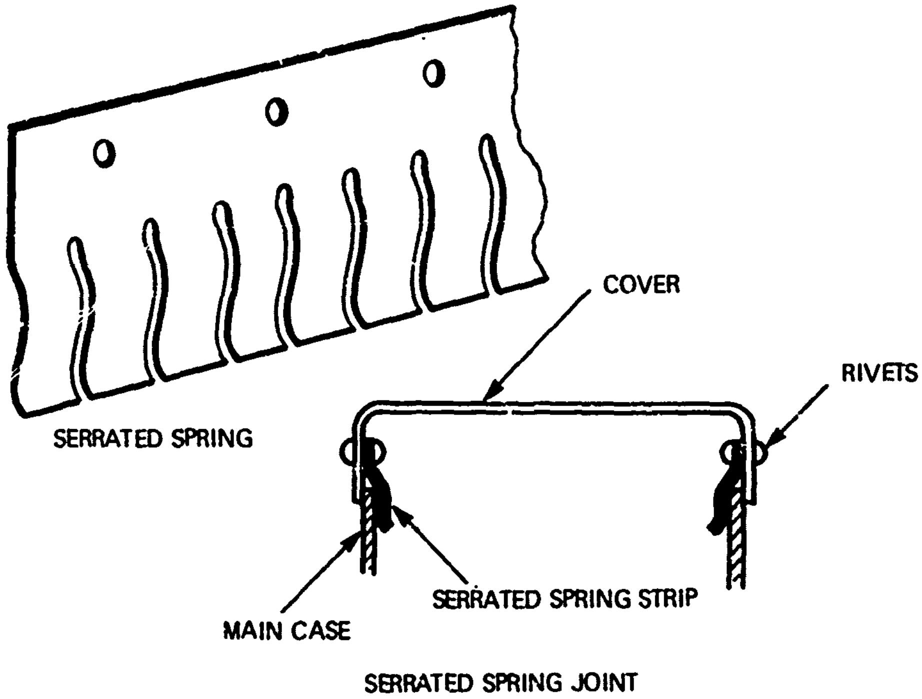


FIGURE 10-44(b) MULTIPLE POINT SPRINGLOADED CONTACT (FINGER STOCK)

Illustrated in Figure 10-45 are examples of joints using conducting gaskets.

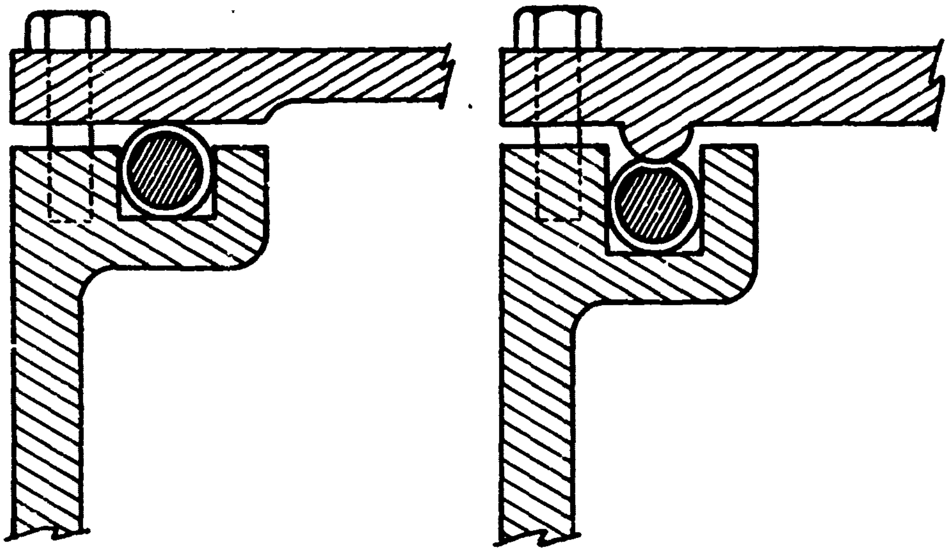


FIGURE 10-45 COVER PLATES WITH CONDUCTIVE GASKETS

One of the primary effects of poor bonding in aircraft systems is the production of nonlinear mixing products of transmitter RF output signals. This is caused by a poor joint acting as an unintended diode. The resulting products can jam communications and radar frequencies.

Precipitation static is a type of noise produced by interaction between the aircraft and particles in the atmosphere through which it is traveling. Parts of the aircraft that are nonconductive or poorly bonded to the main body of the aircraft contribute substantially to such noise.

Cabling and Circuit Routing

Various types of cables are used to interconnect equipment and to connect it to power sources. Several types of cable are available, including:

1. Unshielded wire
2. Shielded wire
3. Coaxial cable
4. Twisted pair
5. Shielded twisted pair

Shielded wire or cable may have single or double shields. Shields are used for many reasons, such as to reduce radiation of signals or interference, to reduce cross-coupling between cables, and to reduce stray pickup by sensitive circuits.

To most effectively shield wires or coaxial cables, bond them well to the ground plane or chassis at each end of the shield. The shield should usually be insulated from ground except at the ends. The grounding connection should be as short as possible for best results. Figure 10-46 shows the effect of different lengths of grounds on the coupling between a shielded wire and a nearby wire. Note that the shortest shield ground (one inch) allows the least signal to couple through.

When overall shielding is used on a multi-conductor cable, it is good practice not only to ground the shield to the connector body, but also to one or more unused pins in the connector. This is illustrated in Figure 10-47. The mating connector pins should be grounded and can also be used to connect to any continuing shield on the connecting cable.

Metal conduit is often used for overall shielding of a group of cables in permanent installations. Couplings and joints in conduit should make good electrical contact. Iron or steel conduit is a better shield than copper at low frequencies, and should be used where high current levels are likely to cause magnetically coupled interference.

Circuit routing is as important as proper shielding in cabling and interconnection of systems and subsystems. The extent of coupling between cables is always inversely related to the distance between the two.

The amount of coupled interference that can be tolerated by a circuit is a function of the level of signals on the victim cable and its impedance. High impedance circuits featuring low level signals constitute the worst case from the viewpoint of susceptibility, while the worst interference sources are those circuits that use high voltage or current levels. Good EMC design dictates the largest possible spacing between cables carrying disparate signal levels. A practical

scheme is one involving routing of high level cables in an entirely different location from those carrying low level signals.

The aircraft environment presents a difficult problem in cabling and interconnection systems. All aircraft systems are limited by space and weight considerations. Lack of space often necessitates close proximity in cabling schemes. The weight limitation places constraint on the amount of shielding that can be used. Both of these factors tend to reduce the effectiveness of EMC design. In aircraft systems, the result is always a compromise between what is generally considered to be good engineering practice and limitations imposed by the aircraft.

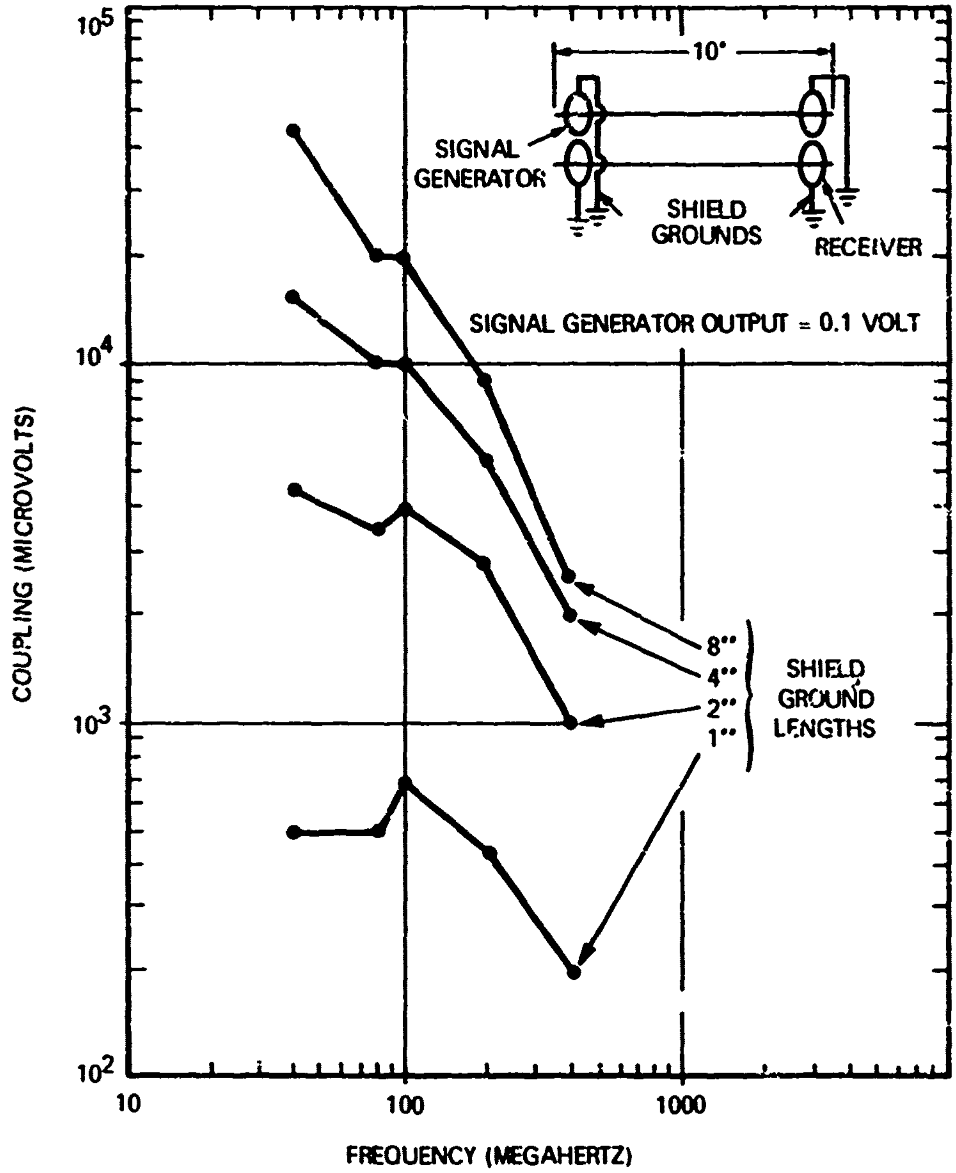


FIGURE 10-46 CABLE COUPLING VS SHIELD GROUND LENGTH.

Grounding

Conducted interference in airborne systems can be reduced if care is taken in the design of the grounding system. It is particularly important that grounded loops be avoided. Illustrated in Figure 10-48 are two alternate grounding systems, single point and multiple point grounding.

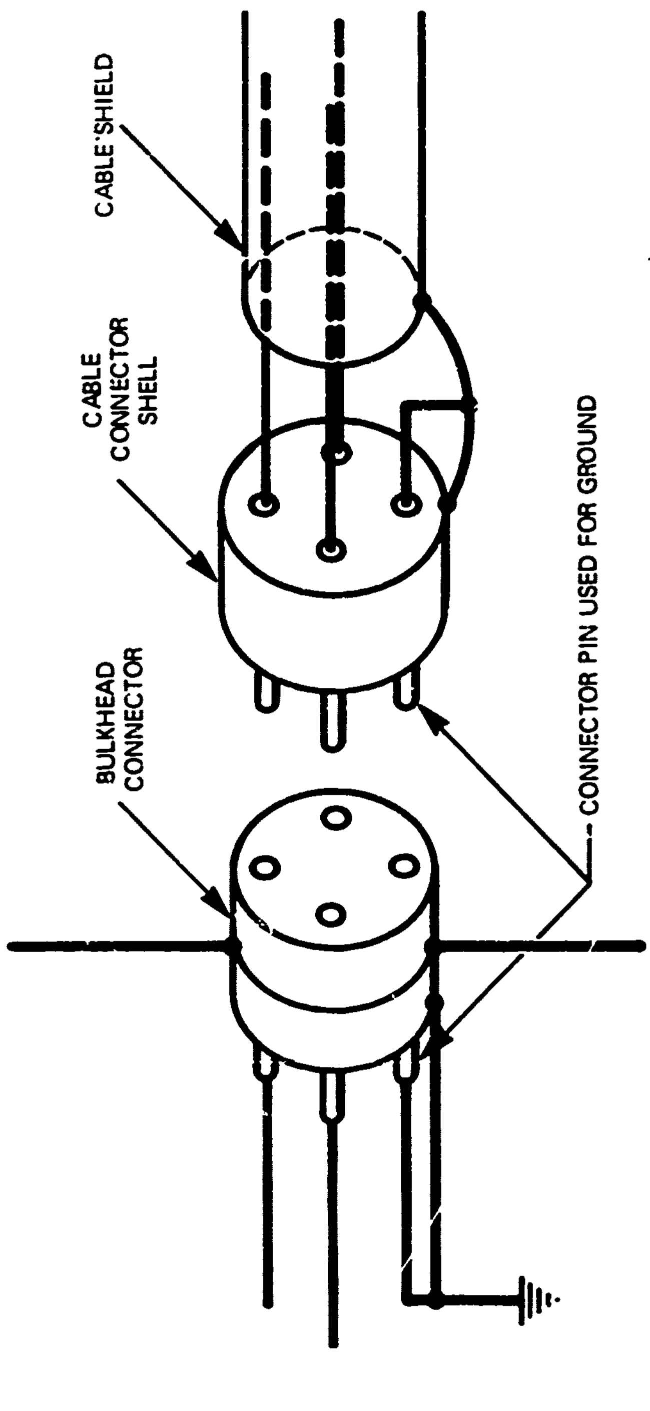


FIGURE 10-47 GROUNDING OF MULTI-CONDUCTOR CABLE SHIELD

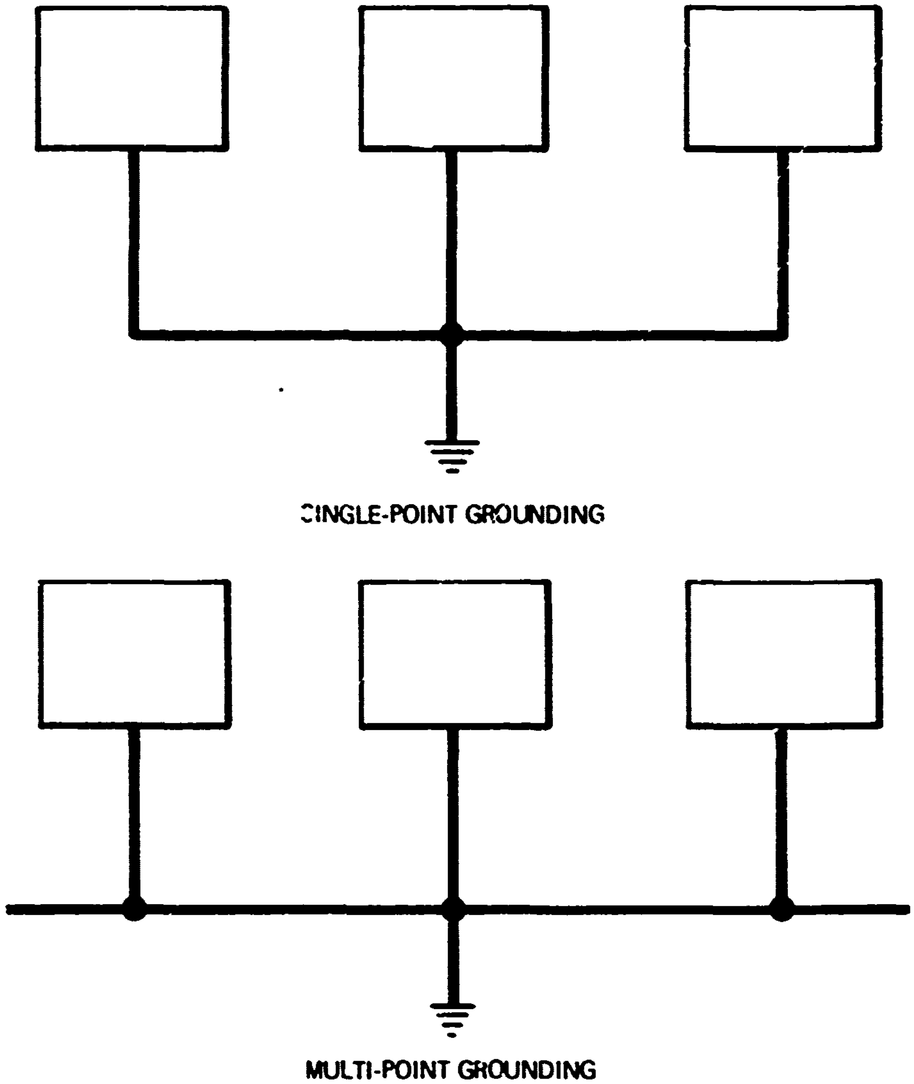


FIGURE 10-46 GROUNDING METHODS

To reduce interference caused by radiation from interconnecting leads in a system, the frames, cabinets, and shields of components in a system should all be grounded at a common point. This is called single point grounding. It prevents unequal ground potentials and thus prevents or reduces ground loop currents between components and equipments. Single point grounding is the ideal. Unfortunately, it is hardly ever possible to realize single point grounding, particularly in aircraft, since long ground lines would be required. The alternate method is to ground each equipment separately to a ground conductor. This is called multi-point grounding. Both single-point and multi-point methods of grounding have advantages, depending on the particular situation.

Grounding connections should have low impedance, which means they should be made of copper, aluminum, or other low resistance material. They should also be as short as possible to keep both resistance and inductance low. A wide, flat conductor or strap also has lower inductance than a round wire with the same cross section. Figure 10-43 shows a comparison of the impedance of a round no. 12 wire with a flat bonding strap. Notice that the strap has about one-fifteenth the impedance of the wire. Three things contribute to this. The strap is wider, shorter and has more surface area than the wire. Single point grounding can be approximated by a multiple point grounding system in which the ground bus is so massive that its resistance is much more than that of the ground strap from any of the equipments attached to it.

Filtering

Filters are an important part of interference signal suppression. Although shields can be rather effective in reduction of radiated signals, wires must still pass through the shield to carry power to the equipment and to carry desired signals in and out of the shield. Filters must be applied to these wires and cables to suppress all signal conduction except that desired.

The filter is an electrical network that allows signals of desired frequencies to pass through, while reducing or attenuating all others. The components in these networks are usually reactive, that is, capacitors and inductors. Resistive elements are generally not used because of attenuation of desired signals.

There are four general types of filters, classed according to which frequencies they pass or attenuate (Figure 10-49). These are:

1. Low pass
2. High pass
3. Band pass
4. Band reject (or band eliminate)

The frequencies at which each filter changes from transmission to attenuation are called the cut-off frequencies, or f_c.

The major type of filter used in power lines and low frequency signal lines is the low pass filter. This filter allows power frequencies (DC, 50-60 Hz, 400 Hz) and ordinary signaling and control frequencies to pass through, but it suppresses harmonics of these frequencies and any other high frequencies.

Often a low pass filter will be of the so-called "brute force" type, where impedance matching is of minor importance, and high attenuation above cutoff frequency is required. The simplest of these is the shunt or bypass capacitor (Figure 10-50). The most commonly used are the shunt capacitor and the inductance input L-type. The values of L and C are chosen to be high enough to keep unwanted currents from flowing in the external load, but not so high as to interfere with wanted signal, control, or power currents. Figure 10-51 is a cutaway sketch of a typical feed-through shunt capacitor. This is intended to be mounted in a shield wall to allow a conductor to pass through the wall, and be filtered at that point. Figure 10-52 shows some examples of feed-through capacitors and their mounting methods. The threaded stud type is very commonly used. An inductance-input L-type filter often has this same type case and mounting.

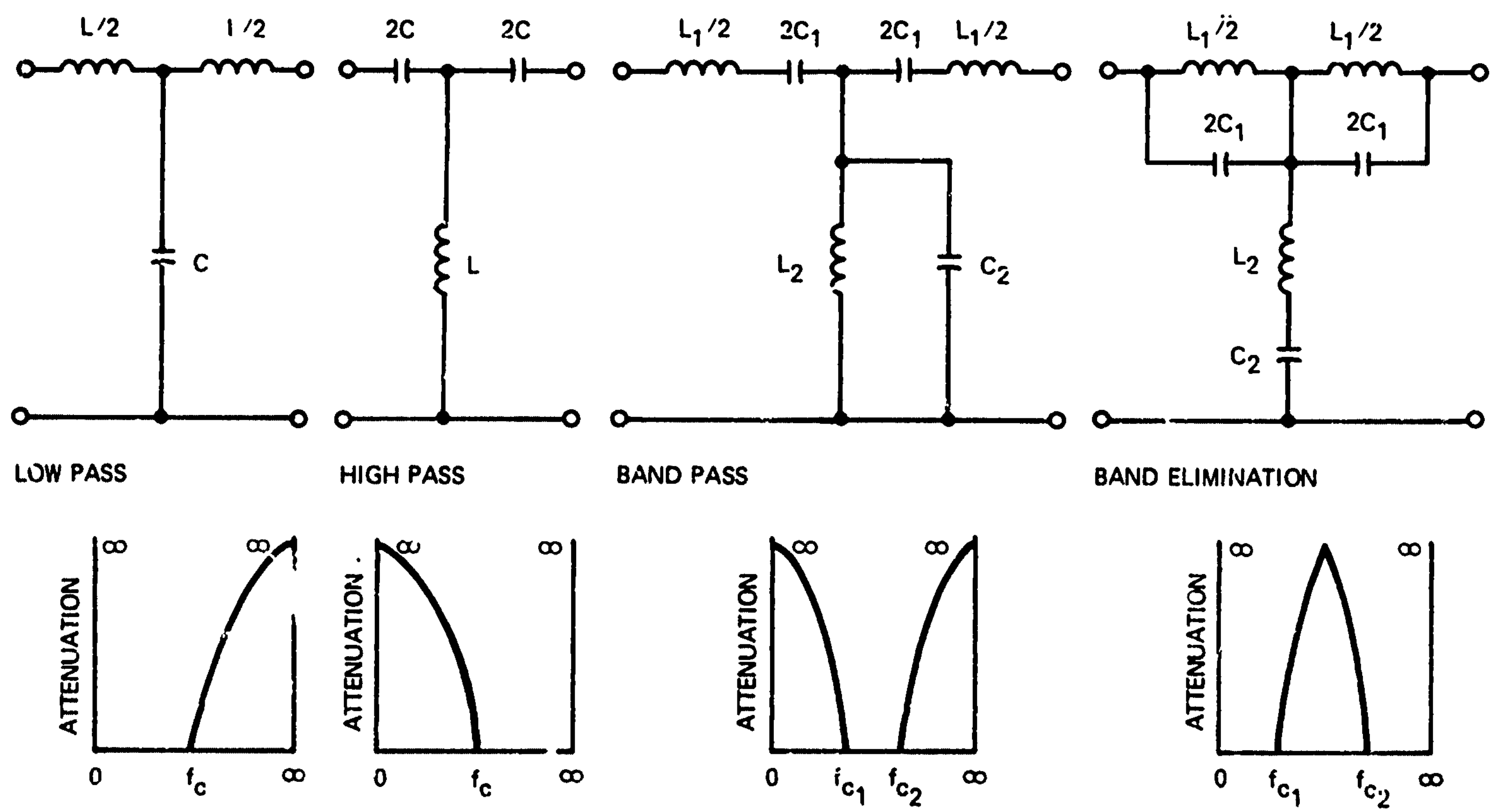


FIGURE 10-49 TYPICAL FILTER SECTIONS SHOWING ATTENUATION AS A FUNCTION OF FREQUENCY

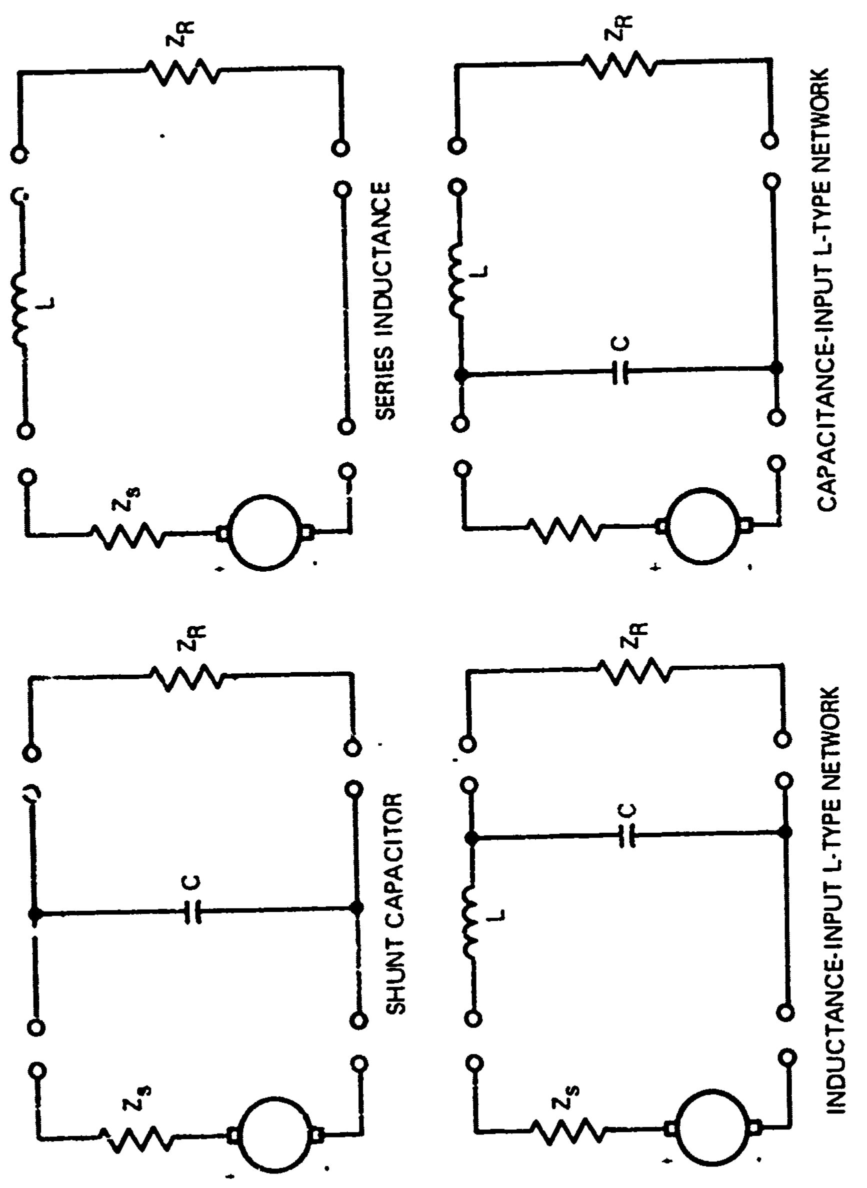


FIGURE 10-50 "BRUTE FORCE" FILTERS.

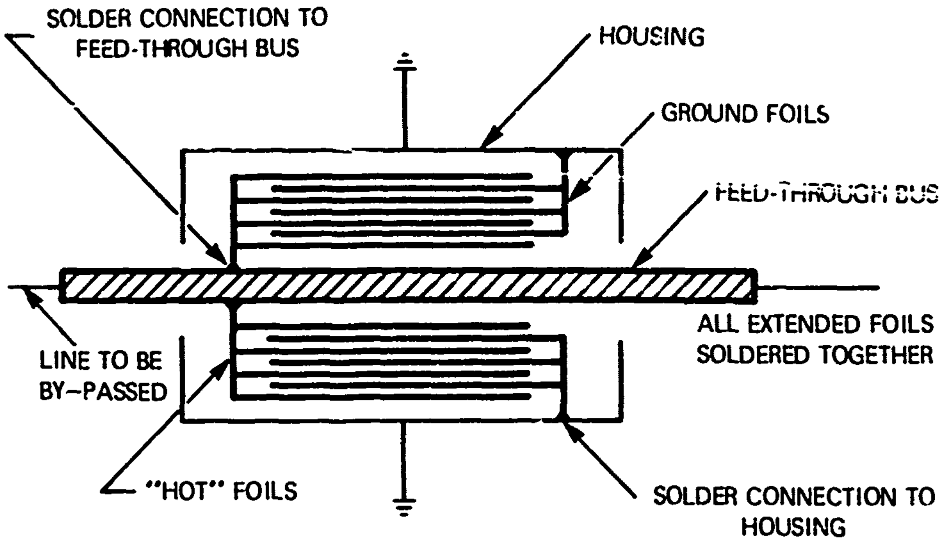


FIGURE 10-51 CUTAWAY SKETCH OF A FEED-THROUGH SHUNT CAPACITOR

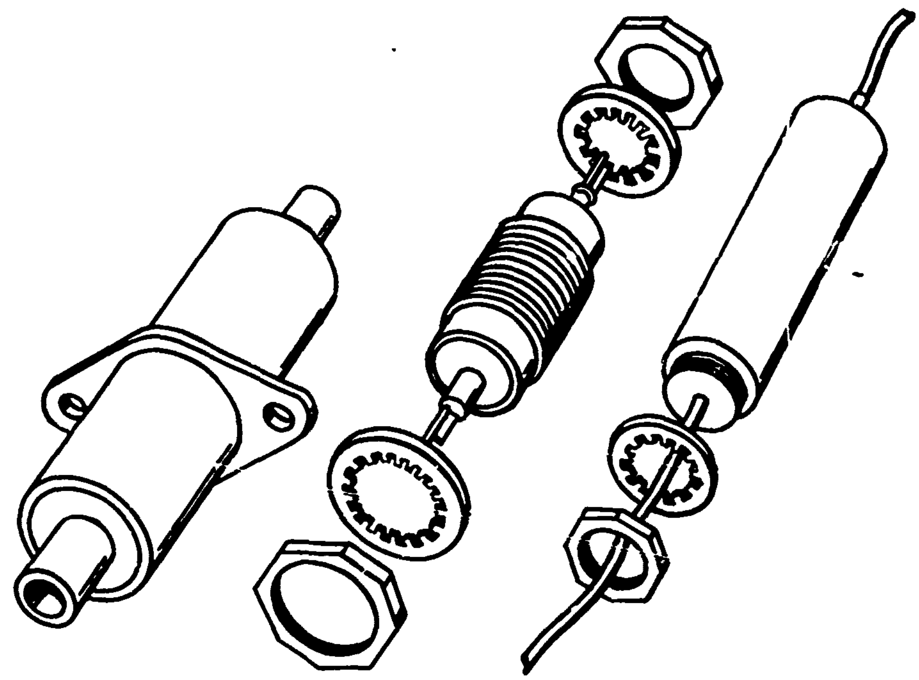


FIGURE 10-52 METHODS OF MOUNTING FEED-THROUGH CAPACITORS

The feed-through capacitor has an advantage over an ordinary capacitor with wire leads. Often the wire leads have enough inductance (although very small) to resonate with the capacitor at some frequency in the range of interest. This makes it very low impedance at that frequency, which is good. However, at higher frequencies, the inductance has higher impedance (reactance) and the attenuation drops off again (Figure 10-53). The dotted curve shows the ideal attenuation for a 0.5f capacitor. Note that the attenuation increases at the higher frequencies. Just below it is a curve for a 0.05f feed-through capacitor. Although it has a slight dip at 50 MHz, it is still rather good. The pointed curve is for the same size capacitor, but with four inches of connecting wire. It resonates at 4 MHz; at higher frequencies the attenuation drops to very low values.

Poor bonding or grounding of a filter can also make it less effective. Figure 10-54 shows a Pi-section filter schematic with a resistor shown in the filter ground return. This resistor represents a poor bond to ground. As shown by the arrows, interfering or unwanted signal currents are allowed to flow through the two capacitors to the external load. If the bond were good or resistance low, the current would be mostly shunted to ground through the left hand capacitor.

Another common cause of poor filter performance is coupling between input and output leads of a filter. This is like locking a door, then leaving a window open. If input and output leads are run close together, capacitive and inductive coupling between them can allow signals to bypass the filter. For that reason, the best filter installation is in a shield wall or bulkhead, with input and output on opposite sides. Next best is when input and output leads are well shielded and kept separate from one another.

Circuit Design Philosophies

In circuit design, there are several methods of minimizing EMC-related problems. Some of these methods concerning transmitters were suggested in the section "Interference Generating Sources." Methods related to receivers are described in the section "Interference Victim Devices."

The general philosophy of circuit design for EMC can be delineated as follows:

1. *For sources* –

   a. Minimize the number and extent of functional frequencies, that is, use the minimum number of frequency conversions in a transmitter

   b. Use nonlinear circuits as much as possible

   c. Use the minimum practical signal level for all functional RF signals

   d. Shape digital waveforms to reduce the spectrum contribution of the signal

   e. Use minimum transmitter power necessary to establish communications or radar operation

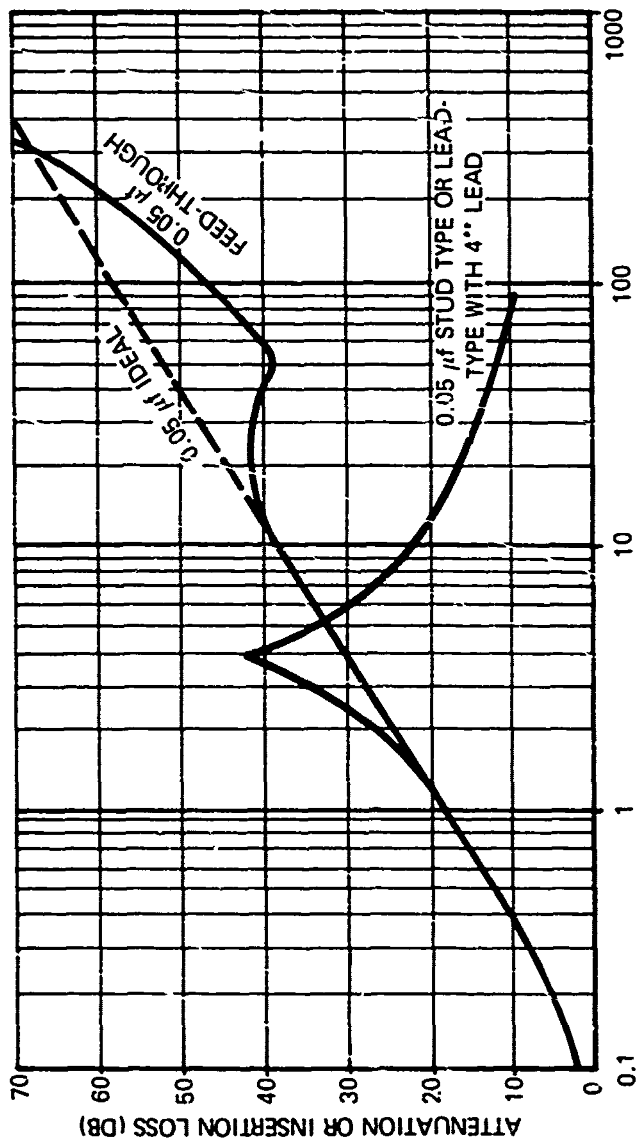


FIGURE 10-53 COMPARISON OF FEED-THROUGH AND LEAD-TYPE CAPACITORS WITH IDEAL CAPACITORS

2. *For victim devices –*
   a. Use maximum practical signal levels commensurate with the design
   b. Maximize the noise margin of digital circuits by using low impedance logic schemes
   c. Avoid using the same signal frequencies as those occupied by functional source emissions
   d. Avoid high impedance and low level circuits
   e. Minimize the use of nonlinear elements
   f. Use "hard" modulation types

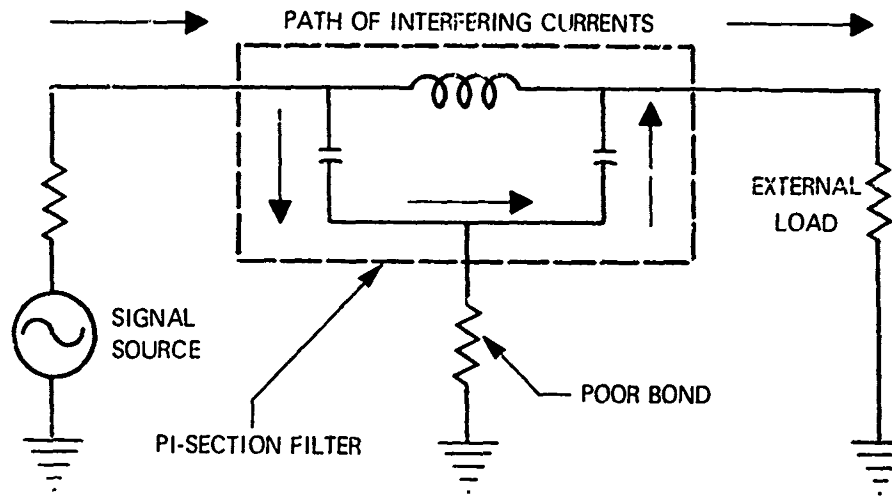


FIGURE 10-54 EFFECT OF POOR BOND IN PI-SECTION FILTER

As can be seen from the above list, some of the same attributes that minimize the susceptibility of a victim device and those that constitute bad design where the device is considered as a source. Again, the rule of compromise applies.

Reliability. Cost. and Mission Considerations

When implemented to the fullest extent, characteristics of all methods of EMC correction thus far suggested lead to reduction in circuit reliability, cost increases of astronomical proportions. or incompatibility with mission goals.

For example. use of low level signaling decreases the basic signal-to-noise ratio in a given signal line, increasing error rates. Shielding adds to the weight of the aircraft and takes valuable space. Extensive experimentation with cable routing and grounding schemes leads to skyrocketing expenses.

It is evident that, because of these factors, a tradeoff must be made between interference tolerance and complexity of suppression methods particularly in retrofit applications. In the latter, it is frequently impossible to achieve total compatibility without virtually rebuilding whole systems, if not the aircraft.

Finally, the mission of the aircraft must be considered. Corrective measures must be used where the mission of the aircraft is endangered by EMC hazards, yet they cannot be used if such use is inconsistent with mission objectives. This type of difficulty often can only be resolved by a waiver.

WAIVERS

Waivers are granted when EMC difficulties cannot be resolved by technical methods. The need of a waiver is indicated when it becomes evident that the airborne system cannot, with reasonable expense, be brought within compatibility tolerances. Waivers are primarily necessary when the system design has progressed beyond the developmental stage and it becomes evident that unforeseen EMC hazards exist. An example of such a situation is when a particular system is installed aboard an aircraft and it is discovered that in the installation it does not conform to RFI-EMI specifications and standards.

When such a situation occurs, it is necessary to conduct a comprehensive reevaluation of the required equipment complement, relative to the mission of the aircraft. The evaluation leads to a decision of whether to delete the offending equipment from the airborne system or to alter the mission profile or operating scenario to reduce or eliminate the EMC hazard. Waiver policy is further discussed under "Test and Validation."

ADDENDUM 10-A

A SURVEY OF AUTOMATED INTERFERENCE PREDICTION TECHNIQUES APPLICABLE TO AVIONICS EMI PROBLEMS

SECTION I

INTRODUCTION

BACKGROUND

It is well known that the later in the evolution of a system a change is made. the more costly the system will be in money and time. In large-scale avionics systems, these costs are often very pronounced. To minimize these excessive costs, it has become important to identify potential problems and to implement necessary changes as early as possible in the system development.

Electromagnetic interference (EMI) conditions within an avionics systems may effect selection and design, equipment location, cable routing, antenna placement, airframe design, operational use, and other factors. A great deal of complexity is involved in the analysis and prediction of intra- and intersystem EMI. This complexity arises from the proximity and density of electromagnetic equipment and energy coupling mechanisms in avionics environments. Problems in performing these analyses are compounded by the scarcity of models providing inputs for technical and managerial decision-making. Furthermore, most of the existing models are manual processes, which require more experience, data generation, and time than is usually available to arrive at a solution.

The requirement to identify EMI conditions early in the system development and to evaluate the complex technical, managerial, and economic factors of alternative corrective actions calls for the use of a computer. However, the definitions of computer hardware and the extent of automation necessary to meet these requirements are extremely complex and will not be discussed here.

OBJECTIVE

Several avionics-oriented manufacturers and government organizations have undertaken the development of automated techniques for the analysis of EMI problems, but these efforts do not include all of the avionics technical and managerial areas. The objective of this study is to identify computer programs designed to treat EMI problems and evaluate their suitability for use as an avionics electromagnetic compatibility (EMC) tool. The study results may prevent costly duplication of existing computer models and point out the specific requirements for computer algorithms tailored for avionics EMI analyses.

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APPROACH

EMI-oriented computer programs were identified through a survey of government and industry sources having some active interest in EMI analyses and avionics systems. Characteristics of these programs were then compared with a set of generalized avionics EMI analyses requirements to determine each program's applicability and utility. The surviving programs have been compared with requirements for an avionics EMI analysis system to illustrate areas that have been covered and those in which new or additional work is required. Particular attention has been given to the problem of transferring existing programs between installations using different computers.

SECTION 2

SURVEY OF AUTOMATED EMI MODELS

NATURE OF THE AVIONICS EMI PROBLEM

Consideration of avionics EMI conditions is characteristically complex. Modern military aircraft contain a remarkable quantity and variety of electromagnetic equipment in a relatively small space. These equipments carry on a multiplicity of functions, some of them simultaneously, and thus must be well designed and coordinated to reduce the possibility of EMI. Placing an aircraft in an operating environment increases potential EMI since other elements of the environment are often of equal or greater complexity. Typical operating environments are airfields or aircraft carriers, flight formations of similar or dissimilar aircraft, and hostile environments in which electronic countermeasures (ECM) are used.

The development of an avionics system includes three basic phases: design, test, and operational evaluation. Within each phase, there are three basic levels of EMI consideration: equipment level (intra-equipment analysis), system level (intra-system or inter-equipment analysis), and environment level (inter-system analysis). The EMI impact of changes proposed or made during the development must be evaluated technically as well as economically with respect to each phase and level of consideration. Table 2-1 identifies the main technical EMI problem areas and relates them to development phase and level of consideration. Significantly, almost all of the problem areas appear in the design phase, during which it is extremely important to produce the most EMI-free system possible. During the survey, any program useful in one or more of these problem areas was considered whether or not it was specifically oriented toward avionics systems.

TABLE 2-1. MAIN EMI PROBLEM AREAS

PROBLEM AREA	PHASE			LEVEL		
	DESIGN	TEST	OPERATIONAL	EQUIPMENT	SYSTEM	ENVIRONMENT
Frequency Planning	X				X	X
Frequency Allocation (J/12)	X				X	
Standards and Specifications Checks	X	X		X	X	
Waiver Analysis	X			X	X	
Data Base	X	X	X	X	X	X
Coupling Analysis	X	X	X	X	X	X
Power Density Prediction	X	X	X		X	X
Intermodulation Analysis	X	X	X		X	X
Spurious Emission & Response Analyses	X	X	X	X	X	X
High Power Effect Prediction	X	X	X	X	X	X
Environment Simulation	X	X	X		X	X
Cull Models	X	X	X		X	X
Degradation Analysis	X	X	X		X	X
Frequency Assignment	X	X	X		X	X
Test Planning		X			X	X

SURVEY RESULTS

The survey began with a search performed by the Defense Documentation Center and examinations of technical conference proceedings, technical journals, and other technical periodicals. Potential EMI program sources identified through these and other procedures (Addendum I) were contacted to obtain information on program capabilities, input and output requirements, and program language.

Most of the programs identified by the survey had some application in one or more area of Table 2-1. It was also observed that almost all of the programs were in the fortran language, which would tend to simplify problems associated with transferring programs between installations and combining programs into larger systems. It was also noted that earlier versions of some programs, a few of which were in other languages, have been combined or expanded into larger fortran programs. Several large programs, typified by the Allen Model maintained by the U. S. Army Electronics Command, were found to be not directly applicable to the avionics problem because they are in other languages, such as algol, or they are specifically oriented toward the solution of non-avionics problems.

A collection of these programs found to be applicable according to Table 2-1 and in the fortran language is given in Addendum II. Each program is identified and abstracted, and the program language, machines it has run on, and documentation references are given. Specific limitations of these programs were too difficult to determine, but generally they are all designed to work from unique data bases or inputs and all provide different types of outputs. In fact, overcoming the input and output limitations will be a more difficult task than reducing technical limitations. Neither program sizes nor storage requirements have been identified since these are highly dependent on the computer used and will be subject to change as programs are combined. Program combinations will tend to reduce storage requirements since many of the programs use similar subroutines and require similar data. Some characteristics of computers identified in the survey are given in Addendum III.

A comparison of avionic EMI program area requirements (Table 2-1) with the resultant available programs is presented in Table 2-2. In this table, the shaded areas represent requirements and the X'ed areas represent available program capabilities. However, since these programs are not components of the

TABLE 2-2. AREAS OF PROGRAM APPLICATION

PROBLEM AREA	PHASE			LEVEL		
	DESIGN	TEST	OPERATIONAL	EQUIPMENT	SYSTEM	ENVIRONMENT
Frequency Planning						
Frequency Allocation (J/12)						
Standards and Specifications Checks	X			X	X	
Waiver Analysis	X			X	X	
Data Base			X		X	X
Coupling Analysis	X	X	X	X	X	X
Power Density Prediction			X			X
Intermodulation Analysis	X		X		X	X
Spurious Emission & Response Analyses	X		X		X	X
High Power Effect Prediction						
Environment Simulation			X		X	X
Cull Models			X		X	X
Degradation Analysis	X		X		X	X
Frequency Assignment			X		X	X
Test Planning		X			X	

same system using identically structured data, the picture given in Table 2-2 is somewhat optimistic. For example, the automated data base and data handling programs available from one source are not necessarily compatible with analytic programs from other sources, although they are all written in the same language. Even so, there is a large disparity between required and available automated capabilities. Table 2-3 shows the application areas covered by each program.

TABLE 2-3. APPLICATION AREA COVERAGE BY PROGRAM

		PHASE LEVEL						PROGRAM APPLICATION AREAS													
PROGRAM	SOURCE	DESIGN	TEST	OPERATIONAL	EQUIPMENT	SYSTEM	ENVIRONMENT	Frequency Planning	Frequency Allocation (J/12)	Standards and Specifications Checks	Waiver Analysis	Coupling Analysis	Power Density Prediction	Intermodulation Analysis	Spurious Emission & Response Analysis	High Power Effect Prediction	Environment Simulation	Cull Models	Degradation Analysis	Frequency Assignment	Test Planning
Cable Coupling Analysis	Boeing	X	X		X							X									X
EMC External Analysis	Grumman					X						X			X			X			
IPP-1	ARC	X		X		X						X						X			
SEMCAP	TRW	X			X	X				X	X	X	X						X		
ISCAP	SFA	X			X	X	X			X		X			X		X	X			
Intra-Vehicle EMC Analysis	MCD-D	X			X	X				X	X	X	X						X		
AVPAK	ECAC	X		X		X	X					X			X						
TIIPS Analyses	ECAC			X			X					X	X		X		X	X	X		
Degradation Analysis	ECAC			X			X												X		
ASP	ECAC			X		X	X	X	X								X			X	
Intermodulation Analysis Model	ECAC	X		X		X	X							X			X		X		

These tables clearly illustrate that few programs are applicable to the test phase, and that no one program covers any one phase or set of application areas completely. But it may be possible to include most of the application areas in the design and operational phases by combining the existing programs into two or three systems programs. Combining programs, however, is not a trivial matter; in addition to accounting for differences in data bases, formats, and language variances permitted or demanded by some fortran compilers, the programmers performing the combination must understand the basic flow and intent of the programs involved. Assuming that these combinations could be achieved, a relatively small amount of additional programming would be required to cover all of the application areas for the design and operational phases and each level of consideration. The major amount of resources will be spent in achieving the required test phase capabilities (Table 2-1). Model specifications, model generation and validation, and model and system programming all need to be performed since there is little capability currently in this area.

SECTION 3

PROGRAM TRANSFERABILITY

GENERAL

The transfer of programs and the data on which they operate from one computer environment to another, at a minimal monetary and temporal cost, is often difficult to accomplish. Every difference in factors involved in a transfer such as computer configuration, operating system, and central processor further complicates the process. The evolution of fortran, cobol, algol, and other high level languages and fast compilers has removed some of the major stumbling blocks in the transfer of applications programs, but cost-effective successes occur infrequently.

PROGRAM TRANSFER

All of the programs included in Addendum II are in the fortran language. However, this does not guarantee that transferring the program from its current operating environment to another installation can be accomplished with ease. Although the fortran language, and consequently, most fortran programs, and more importantly fortran compilers conform to standards established by the American National Standards Institute, there are still some computer-dependent areas not standardized. The majority of these pertain to input and output functions such as formal specification, read and write statements (especially for mass storage devices), and data element length and specifications. One other main area of incompatibility is the availability of fortran statement types and subprograms, such as the cosine (COS) operator, in all compilers. Table 3-1 shows the availability of statement types in several different IBM fortran compilers. In addition to these, other incompatibilities may have been introduced by a programmer

taking advantage of the system software available at his installation such as data packing to save on storage requirements.

(TABLE 3-1 TO BE PROVIDED)

Perhaps the best method to carry out the physical transfer of a program between installations is via 80 column Hollerith card decks containing the source (fortran language) program. Transfers of source programs by magnetic tapes may lead to problems in varying number of tracks, writing density, codes, parity checks and label blocks. Once the program has been transferred by cards it can be read into the second installation's compiler quite readily. Undoubtedly, the compiler will produce many diagnostics that indicate some incompatible areas. After this initial run, it is good practice to study the program intensely and attempt to correct as many problems as possible, taking into account the peculiarities of both computer systems rather than to concentrate on only the diagnostics obtained in the first run. The reason for this is that many compilers work on several levels, not all during the same run. Thus, a particular solution to a series of first level diagnostics may be completely negated by runs through subsequent levels. A compiler run that results in no diagnostics does not guarantee an error-free program, since no fortran compiler claims to be able to detect all possible errors.

Once several programs have been successfully transferred, debugged, and are operating, it may be desirable to combine them in some fashion. This, too, is difficult since even programs obtained from the same source are not necessarily compatible with each other. Compatibility in this context refers mainly to data required, methods of delivering it to the main program or subroutines from various locations, and methods of producing outputs. Minor problems include ensuring that the same variables in these programs have the same names.

DATA TRANSFER

Virtually every program requires some form of input data. Many of the programs in Addendum II shared common data requirements. But these programs, developed in an uncoordinated manner, expect input data in different ways. One program may expect receiver antenna gain before bandwidth, and another may expect the same data in reverse order; one program may expect transmitter power in watts, and another may expect power in dBm; one program may require an antenna pattern and another may synthesize it.

To operate these programs economically on one computer and to obtain the maximum use from data generated by other users, common data bases are required. These data bases may include equipment characteristics, military standards and specifications, environmental equipment data, and deployment or scenario libraries. The programs and the data will have to be mutually adjusted in format, content, and position to ensure compatibility. Each data base also requires programs to assist in maintenance functions such as additions and deletions, data element corrections, and in some cases, data generation.

Because the quantity of applicable stored data is so vast, the most economical means of data transfer is via magnetic tape. Since tape formats are bound to differ between installations, special programs to decipher the data encoded on different tapes will be required. This cost, added to the cost of the studies required to define the data bases, change the programs to accommodate the data,

and maintain the data bases results in a large expenditure of manpower and funds, an expenditure which may be great enough to deter the transfer of data and consequently the transfer of programs for which the data are required.

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS AND RECOMMENDATIONS

The computer programs listed in Addendum II are all applicable to the avionics EMC problem. Many of the programs have overlapping data requirements and analytic capabilities and all have unique features. The value of these programs and their associated data bases must be determined in the light of NAVAIR's automated avionics EMI program requirements, and these requirements have not yet been defined.

The next step of this process should be the definition of NAVAIR's EMI ADP requirements and consideration of those portions of the EMI problem that can best be handled by NAVAIR, the avionics systems manufacturers, and organizations such as ECAC. The high costs of program and data base transfer are major factors in making this definition.

Once NAVAIR's specific requirements are defined, further decisions will be required to determine which programs and data bases are to be transferred, which existing programs should be completely rewritten for the NAVAIR installation, and which problem areas not presently automated should be programmed.

ADDENDUM I

EMI PROGRAM SOURCES

Naval Air Test Facility

Air Force Avionics Laboratory

Rome Air Development Center

U. S. Army Electronics Command

Electromagnetic Compatibility Analysis Center

National Aeronautics and Space Administration

Federal Aviation Administration

Boeing Company

McDonnell-Douglas Corporation

Grumman Aerospace Corporation

Lockheed Missiles and Space Company

General Electric Company

TRW Incorporated

Atlantic Research Corporation

Bell Aerosystems

Lockheed Electronics Company

Sachs-Freeman Associates

University of Michigan

University of Pennsylvania

Western Area Frequency Coordinator, Point Mugu, California

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ADDENDUM II

PROGRAM ABSTRACTS

Program	Cable-Coupling Analysis
Reference	AFAL-TR-65-142 Computer Analysis of Cable Coupling for Intra-System Electromagnetic Compatibility B. L. Carlson, W. R. Marcelja, D. A. King Boeing Company, May 1965
Abstract	This program is used in the analysis of intra-system EMC of an avionics system in the early design stages. The primary concern is cable-to-cable and common impedance coupled EMI in the 10 Hz to 400 MHz frequency range. In the reference, consideration is given to the development of a program to determine the critical test points to be monitored in a system test and to determine the design and test requirements which need to be placed on equipment for interference control within a system.
Language	Fortran
Computer	Univac 1107

Program	EMC External Analysis
Reference	EA-6B-SYR67-7 EA-6B EMC Analysis Report No. 1 J. De Simone, D. C. Engle, P. Woltmann Grumman Corporation June 1967
Abstract	This program calculates effects in receivers of transmitted energy coupled through paths external to an EA-6B aircraft skin. The program contains math models of avionics equipment and, in the absence of empirical data, will calculate the important parameters required to develop the emission and susceptibility signatures for the equipment. The program models:

Transmitter harmonic and other spurious outputs

Transmission line and filter characteristics

Free space propagation with near-field and shading adjustments

Receiver responses from the antenna terminals to the second detector

Antenna patterns from a library of prestored data

References modulations to the CW case

The program is capable of defining problems in the time and frequency domains to establish mission capabilities when related to intra-aircraft, multiple aircraft, or multiple ground emitter environments. The program has been used to predict conditions under which EMC problems will occur, and to provide data useful in the development of a comprehensive test frequency selection plan.

Inputs	User-supplied transmitter and receiver data and locations, and computer-stored antenna patterns library.
Outputs	Predicts worst-case spurious response or intermodulation/harmonic problem for each transmitter-receiver pair.
Language	Fortran
Computer	IBM 360/75

Program	Interference Prediction Process (IPP-1)
Reference	RADC-TR-66-1 Interference Notebook RADC-TR-70-29 IPP-1 Program Improvements
Abstract	The basic IPP-1 consists of three main routines:

Rapid cull

Frequency cull

Detailed analysis

The rapid cull routine determines transmitter fundamental interference level, receiver fundamental interference level, transmitter fundamental equal to receiver tuned frequency interference level, and interference levels for off-fundamental cases which are stored for later use. The frequency cull is used to further reduce the output of the rapid cull on the basis of exact frequency information using transmitter modulation curves and receiver selectivity curves

to obtain bandwidth corrections. The detailed analysis routine uses the output of the frequency cull and incorporates into the analysis antenna rotation factors, detailed near-field coupling factors, time independent or dependent antenna gain correction factors, and detailed propagation calculations. Improvements made to the IPP-1 include input and output modifications, development of a frequency-distance equipment criteria routine, development of techniques for providing propagating path loss models, and near-field analysis of arrays by matrix methods.

Language Fortran

Computer GE-635

Program Specification and Electromagnetic Compatibility Analysis Program (SEMCAP)

References Systems Approach to Achieving Intra-System EMC Utilizing Computer Techniques
W. R. Johnson, J. A. Spagon
TRW Systems Group
September 1970

TRW Report No. 11176-H245-R0-00
Apollo 11 Computerized EMC Analysis
R. H. Parry
TRW Systems Group
June 1969

TRW Report No. 08900-6001-T000
Development of a Space Vehicle EMI/EMC Specification
June 1968

Abstract This program performs an EMC analysis between modeled generator and receptor circuits for various means of interference transfer. The program calculates the spectrum of the generator circuits and transfers the energy via a transfer function to the receptor terminals. Received energy is compared with the receptor circuit threshold to determine compatibility. Contributions of each generator are summed to determine whether the receptor is compatible with the sum of generator sources modeled. Generator types consist of single frequency (CW), trapezoidal pulse train, ramp step, trapezoidal single pulse, and spectral density voltage or current generators. Filter types may be low-, high-, or bandpass. Transfer functions may be mutual inductance, mutual capacitance, electric field, or magnetic field coupling. Receptor

field response types are E-field antenna and wire, H-field antenna and wire, and wire only. In addition to performing EMC analysis the program also can generate a set of specification limits for each type of interference transfer mechanism, and perform a waiver analysis based on subsystem EMC test data. Only linear cases are considered and thus spurious responses, intermodulation, etc. are not specifically accounted for. The program performs a power analysis and is not necessarily applicable for determining degradation with modulated signals.

Language	Fortran and one machine language subroutine
Computer	CDC 6500

Program	Intra-system Compatibility Analysis Program (ISCAP)
Reference	ESD-TR-70-261 Intra-System Compatibility Analysis Program H. Sachs, E. Freeman, R. Parlow Sachs-Freeman Associates
Abstract	This program was written to support SPOs and planning offices in defining, evaluating, and managing system EMC programs. The capabilities include:

Specification compliance evaluation

Spectrum overlap/antenna-coupled interference potential

Non-antenna coupled interference potential

The program consists of the following routines:

MIL-STD-469 check MIL-STD-188B check	compare equipment parameters with standards

Spectrum overlap and amplitude check   computes transmitter fundamental/harmonic overlap, spurious overlap, and coupled signal level

Receiver analysis   computes in-band and out-of-band spurious responses, cross-modulation, and receiver intermodulation

Close coupling   handles wire, case, and antenna narrow or broadband conducted or radiated energy; computes E-field

susceptibility for single or multiple couplets and sums voltages in a receptor from all generators

Language Fortran and one machine language subroutine

Computers IBM 7030 stretch
Univac 1108

Program Intra-Vehicle EMC Analysis

Reference G. Weinstock, M. Siegel, Dr. J. Bogdanor
McDonnell-Douglas Corporation
September 1970

Abstract A computer program for analyzing coupled EMI effects among equipment on an air vehicle is being developed. (Program Development: Apr 70-Mar 71; Program Verification and Report: Mar 71-Sep 71.) The program will contain models for predicting the effects of:

Antenna-to-antenna coupling

External field-to-wire coupling

Wire-to-wire coupling

Box-to-box coupling

Box-to-wire coupling

The antenna coupling model provides results for both near and far field cases and also accounts for shading effects introduced by obstacles such as a wing. The wire coupling model features spectrum generation routines for common waveforms (rectangular pulse, step function, spike, trapezoidal pulse) and can accept any twisted and/or shielded wire configuration and user-supplied spectral data. The program can be used as an aid in:

Producing EMC design requirements

Formulating subsystems detail specifications

Recommending military specification modification

Influencing design changes

Justifying waiver requests

Determining changes in EMC provisions

Various inputs in these models are made with "easy to use input data formats." Model outputs provide data on interference frequencies, EMI margin, degree of shielding, receive signal.

Language	Fortran
Computers	IBM 7094 IBM 360/85 GE 420 timesharing

Program	Airframe Cosite Analysis Model (AVPAK)
Reference	ECAC-TN-011-199 Electromagnetic Compatibility Analysis Center July 1970
Abstract	A computer program written to model communications and radar equipment on an airplane in order to identify possible cosite interference problems which may exist between such equipment. Each transmitter and receiver pair is examined to see if the effective signal from the transmitter is greater than the receiver's susceptibility threshold. A list is presented which summarizes all of the equipment pairs with possible interference. This model approximates worst-case conditions in order to eliminate equipment pairs which could not reasonably present interference.
Language	Fortran
Computer	Univac 1108

Program	THPS Analyses
References	ECAC-TN-009-99 ECAC-TN-009-102 ECAC-TN-009-123 Electromagnetic Compatibility Analysis Center
Abstract	These programs are used to reduce an environment of electronic equipment to only those equipment pairs (couplets) that present a potential interference problem. A decision on interference condition is based upon one or more of the following factors:

Power density

Interference-to-noise ratio

Signal-to-interference ratio

Minimum separation distance to avoid interference (mobile cases)

Environments of transmitters and receivers are quickly processed using simplified models and assumptions of linearity, etc. The main input medium is the ECAC Environmental File (E-File).

Language Fortran

Computer Univac 1108

Program Degradation Analysis

Reference ECAC-TR-65-1
Electromagnetic Compatibility Analysis Center

Abstract The degradation modeling capability is used to extend an interference prediction (interference-to-noise ratio, signal-to-noise ratio, signal-to-interference ratio, etc.) to a degradation evaluation. These models provide the means by which the engineering measures (power levels, frequencies, etc.) employed in receiver analysis are translated to measures of intelligibility. The receiver location or interface at which the degradation evaluation is made is at the IF output. The interference effects are obtained at the decision mechanism (human observer, a threshold circuit, etc.).

Language Fortran

Computer Univac 1108

Program Assignment Search Program (ASP)

Reference Electromagnetic Compatibility Analysis Center

Abstract ASP is an automated method of finding a frequency assignment which satisfies the user's criteria expressed in the form of frequency resources lists and Frequency/Distance (F/D) curves. The program will search for a successful assignment, "backing-up" or "assigning" previously made assignments when necessary. Given enough time, all possible ways of making an assignment could be considered. If ASP cannot make an assignment, the user may re-

lax his criteria and try again: it is the user who decides when and where the trade-offs are to be made, not the model. Some special modifications have been made to ASP to allow it to handle tactical HF assignments and rapidly change some predetermined criteria without user intervention. This modified program exists as a separate version.

ASP has several limitations. One is the difficulty associated with providing high quality F/D curves for each different nomenclature or equipment pair, especially when considering directional antennas and especially in large problems. Another is the excessive computer time that may be required to arrive at a "best" assignment. In the HF version, ASP is not equipped to make proper frequency selections based on propagation considerations. The program requires discrete locations, which are difficult to determine for tactical problems. The program, due to the search scheme, may tend to long running times.

Language	Fortran
Computer	Univac 1108

Program	Intermodulation Analysis Model
Reference	ECAC-IN-009-095 Electromagnetic Compatibility Analysis Center
Abstract	This program is used to identify potential intermodulation cases based on both power and frequency considerations. The calculation of the intermodulation power level is based on empirical data available through spectrum signature reports. The program lists potential intermodulation cases identified with indication of frequency and power of interfering signal. Only second, third, and fifth order mixes are considered.
Language	Fortran
Computer	Univac 1108

Program	Mathematical model: Calculation of Near Field of Circular Aperture Antenna Using Geometrical Theory of Diffraction
Reference	T. E. Cherot, Jr., Western Area Frequency Coordinator, Point Mugu, California 93042; Member, IEEE

Abstract	A tutorial account of the geometrical theory of diffraction is presented, and as an application of the theory, the near field of a circular aperture antenna is calculated. This method is useful in calculating accurately the field in regions far from the antenna axis. It is particularly useful because of its simple mathematical formulation, which readily produces numerical results.
Language	Fortran IV
Computers	IBM-7094 and other Fortran IV Systems

Program	Mathematical model: A Spectrum Prediction Technique for AM Pulses of Arbitrary Shape
Reference	Steve Gutsche, Western Area Frequency Coordinator, Point Mugu, California 93042
Abstract	The accuracy of predicting spectra for pulsed AM systems is greatly improved by merely describing the time-domain signal with more accuracy. Specifically, a series of straight lines is used to approximate an arbitrary signal shape. Experimentally, a pulse-shaping network and spectrum analyzer were used to generate and record various time- and frequency-domain shapes. These results were compared to the theoretical plots generated by the straight-line approximation technique. The improvement of this technique over the method of assigning a perfect square pulse is illustrated by plots and photographs. The theoretical results are almost good enough to eliminate the need for a frequency-spectrum signature if the signal can be observed in the time domain by an oscilloscope.
Language	Fortran IV
Computers	IBM-7094 and other Fortran IV Systems

Program	Mathematical model: Calculation of the Near Field Antenna Patterns of Aperture Antennas
Reference	T. E. Cherot, Jr., Western Area Frequency Coordinator, Point Mugu, California 93042; Member, IEEE
Abstract	The near field antenna patterns of aperture antennas have been calculated using a computer program. The analysis is based upon the semi-simulative method derived by Hu[1]. The method is unique

because of the simplicity of the theoretical basis. The flexibility of this method allows the user to perform near field calculations for most practical situations.

Language	Fortran IV
Computers	IBM-7094 and other Fortran IV Systems

Program	Mathematical model: A Spectrum Analysis of PCM/AM-FM and PCM/FM-FM Telemetry Signals
Reference	Steve Gutsche, Western Area Frequency Coordinator, Point Mugu, California 93042
Abstract	This describes the development of a PCM/FM-FM telemetry signal and deals with the spectrum characteristics of this particular waveform. A computer approximation technique is used to allow the time signal to be Fourier-transformed to the frequency domain. To verify the approximation, various spectra are calculated by this method and compared to experimentally observed results. An accurate prediction of PCM/FM-FM spectra, as furnished by this technique, is especially important because of the anticipated growing use of this format by telemetry users.
Language	Fortran IV
Computers	IBM-7094 and other Fortran IV Systems

Program	Mathematical model: Frequency Management Program
Reference	Ken W. Canaga, Western Area Frequency Coordinator, Point Mugu, California 93042; Member, IEEE
Abstract	This program, available in Fortran IV for the IBM 7094 and the UNIVAC 1230, creates and maintains a tape library of transmitter and receiver characteristics within a given geographical area. From this data base, it analyzes interference and personnel hazards. The primary advantage of this program over similar models is its ability to handle large numbers of transmitters and receivers in one analysis, which makes it suitable for use in a dense electromagnetic environment where individual hand calculations are too slow.
Language	Fortran IV
Computers	IBM-7094 and other Fortran IV Systems

ADDENDUM III

SOME SURVEYED PROGRAM COMPUTER CHARACTERISTICS

EXPLANATION OF HEADINGS

Internal Characteristics

Solid State: If the computer is built with primarily solid state devices such as transistors, distinguished from non-solid state devices such as vacuum tubes, a "Y" appears in this column. Solid state devices are generally more reliable than non-solid state devices.

Number System:

Number Base: the number base the machine uses internally (either binary, octal, or decimal).

Bits/Digit: the number of binary bits per digit (digit is either a binary, octal, or decimal digit; see *Number Base*).

Digits/Alphabetic: the number of digits used to represent an alphabetic character.

Word Length: the number of numerical digits per machine word.

Memory:

Number of Words: the number of machine words contained in the memory: may be broken into two or more memory types or two or more lines. Whenever the machine word length is "variable," the *Number of Words* refers not to the number of machine words but to the number of digits.

Type: memory type, such as magnetic drum (abbreviated/"drum"), core storage or delay line.

Access Time: the time required to retrieve information from the memory

Timing - (Add, Multiply, Divide): the average time required to get and complete one operation instruction.

Machine Programming:

Number of Instr.: the number of distinct instructions in the machine's repertoire.

Addresses/Inst.: the number of operand addresses per instruction.

No. Index Registers: an "O" indicates no indexing possible; a "Y" indicates that indexing is possible but information as to the number of index registers was not received.

Indirect Addressing: "Y" indicates indirect addressing is possible.

Floating Point: "Y" indicates that the machine can perform in a floating-point mode. (Floating-point arithmetic can be programmed on all machines.)

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Input and Output

Magnetic Tape:

No. of Units: maximum number of tape transports which can be directly connected to the computer.

Tape Density: characters per inch.

Tape Speed: speed of reading or writing on tape.

Words/Tape: capacity of a reel of tape.

Punched Cards: speed of reading and punching cards.

Paper Tape: speed of reading and punching paper tape.

Printer Speed: speed of printing, complete lines printed per minute.

Abbreviations Used

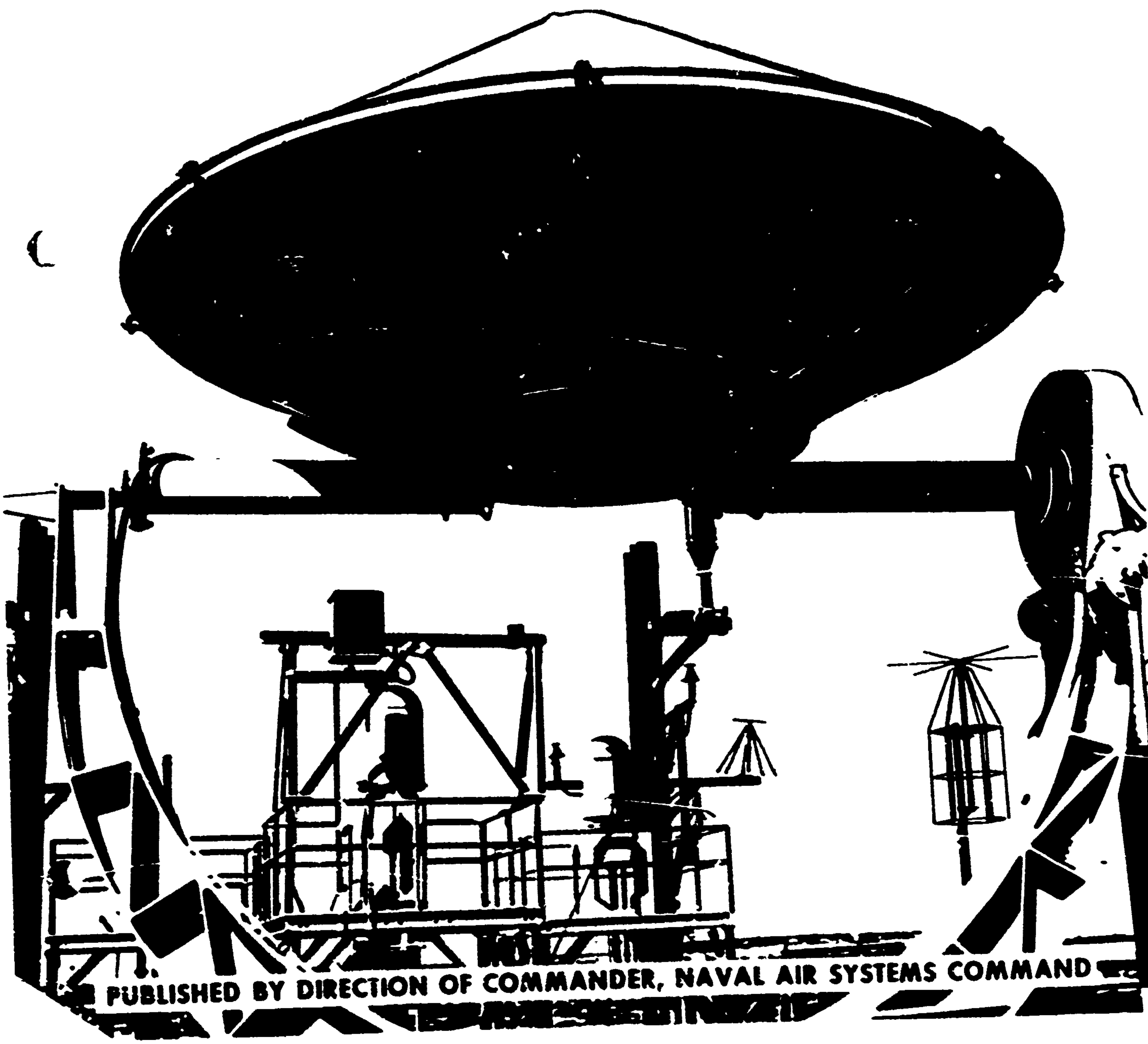
B – binary
D – decimal
I/O – input/output
K – 1000
KK – 1,000,000
m – millisecond, thousandth of a second
n – nanosecond, billionth of a second
N – no, none
P – punch, output
R – read, input
u – microsecond, millionth of a second
V – variable
Y – yes

NAVAIR 5335

NAVAL AIR SYSTEMS COMMAND

ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 11



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NAVAIR EMC MANUAL

CHAPTER 11
GROUNDING AND BONDING

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INTRODUCTION

Grounding and bonding do not refer to the same procedure or have the same purpose. Grounding is the electrical connection of return circuits to the reference ground plane; bonding is the electrical connection of conducting surfaces into one homogenous ground plane. The two terms should not be confused.

Grounding and bonding are generally concerned with the same problem: establishing a low resistance path to a reference potential in order to establish signal and power voltages.

Grounding provides an electrical conductive path between the circuit to a reference point. The reference point can be earth, the equipment enclosure, or the vehicle structure itself. Good grounding techniques depend on good bonds. A uniform grounding philosophy is mandatory to avoid conductive coupling, low impedance ground loops, and hazardous conditions.

Electrical bonding mechanically connects certain metal parts to make a good low-resistance electrical contact. Bonding is required to insure that a system is electrically stable, relatively free from the hazards of lightning, static discharge, and electrical shock, and to assist in the suppression of RF interference. Usually, the resistance of electrical bonds should be on the order of 2.5 milliohms.

GROUNDING DESIGN OBJECTIVES

The term "ground" is derived from early use of the earth as a sink for electrical charge and as an essential element of the Marconi antenna system. The ground system, for earth-based equipment, includes structural elements as well as equipment cabinets, chassis, and connecting wires all connected to the earth and referencing the earth potential to protect personnel.

"Ground" as applied to an airborne system or aircraft cannot refer to the earth, unless the aircraft is resting on the earth and a ground line is attached. When the system or aircraft is airborne, the aircraft structure is considered "ground" because it must provide that which the earth offered to the ground-based system. Fortunately, airframes are made of good electrical

conducting materials such as alumimum alloys that are second only to copper as inexpensive capable conductors. Consequently, the airframe has one of the basic attributes of a good ground system–good conductivity. The structure that forms the ground system includes the racks that hold the drawers, the conduit, ducts, trays, consoles, control panels, instrument panels, mounting fixtures, brackets, and pylons.

Circuitry, which makes use of the grounding system, includes the wires, shields, components, and the immediate metal chassis to which decoupling capaciters are connected. The interface between circuitry and structure is the part of the ground system that must be carefully planned. The objective in laying out this part of the ground system is to avoid common mode coupling between the various circuits where performance would be degraded. In general, this part of the ground system is designed so that the various branches are connected to the structure at a single point, which is designated the Vehicle Gound Point (VGP). A number of VGPs may be used if the structure is large. This raises problems where some circuits have been designed with input and output circuits not isolated from ground. The power supply should also be designed to isolate the load from ground. This may be one of the important functions of the power supply. A number of small power supplies may be used instead of a few large ones so that loads may be isolated not only from ground but also from each other. This type of isolation is required so that the ground system will not be compromised with undesired shunt paths.

It is important that the designer consider the ground system characteristics across a broad frequency spectrum with particular emphasis on the operating frequencies. At these frequencies the inductance of ground leads and the capacitance of the circuit chassis and ground leads to the structure are important considerations. Inductance can be controlled using metal straps or tubular conductors of adequate size. Capacitance effects are not as readily controlled. To reduce capacitance, cable and chassis separation must be increased or size must be reduced or both. Miniaturization of circuits offers the most attractive way of reducing capacity effects.

The ground system is complex and must satisfy a number of different requirements:

(1) Personnel safety as related to the electrical power system
(2) Lightning protection of personnel and equipment
(3) Electromagnetic compatibility by providing a quiet common bus for grounding electronic equipment

To suppress interference through an effective grounding system, all ground leads for shielding, circuit reference points, and structural components within the system must be maintained at the same potential. This is generally done by establishing separate ground reference systems for each equipment or group of equipments and combining these separate grounds at one common reference point or plane. The purpose of separate ground systems is to prevent any electromagnetic interference generated in one unit of the system from being transferred to other units through a common ground impedance. If potential differences are not permitted, interference currents cannot flow and undesired

signals cannot be radiated or conducted to susceptible parts of the system. However, because no conductor has zero impedance, the ideal situation of zero potential difference can only be approached, never completely achieved. The larger the aircraft structure as a ground system, the more difficult it is to achieve this ideal.

Besides the ohmic resistance of the conductor material, there is an additional resistive component produced when a conductor carries an alternating current. This AC resistance depends upon frequency and can become very high relative to the DC resistance. One of the main reasons for high AC resistance is a phenomenon called "skin effect." Detailed calculations of this effect are quite complicated but have been measured and tabulated for most practical conductor configurations and appear in numerous engineering handbooks. Skin effect is present at all frequencies but becomes more noticeable at high frequencies. Following is a brief explanation of the effect.

Fluctuation of current in a conductor produces a proportionally moving magnetic field:

$$\frac{di}{dt} = \frac{Nd\phi}{dt} \qquad (11\text{-}1)$$

where:

ϕ = flux lines (webers)
N = number of turns in a coil
i = current in amperes
t = time interval

As this magnetic field moves across the conductor, it induces an electric field in a direction opposite to the original current flow. Because more magnetic flux lines of the moving field will link the center of the conductor than link an area near the surface, the induced counter-EMF, and consequently the impedance, will be greatest near the center. This forces the current to the skin of the conductor where it is encircled by the smallest number of flux lines. Figure 11-1 shows the flux lines and the current distribution resulting from skin effect for conductors with different cross-sectional configurations.

The effective AC resistance can be found by assuming that all of the current is flowing in a uniform shell of depth δ around the cylindrical conductor. The hypothetical skin depth is δ and is defined as the depth at which the current density is 1/e of the density at the surface of the conductor (e = 2.718 and 1/e = 0.367879).

$$\delta = 5033\sqrt{\frac{\rho}{\mu f}} \text{ centimeters} \qquad (11\text{-}2)$$

where:

f = the frequency of the AC current in Hz
ρ = the resistivity of the material in ohm-centimeters ($\rho = 1.724 \times 10^{-6}\,\Omega$-cm. for copper)
μ = permeability of the conductor ($\mu = 1$ for copper)

The assumption that all the current is within δ of the surface implies that all the current is flowing in a shell of cross-sectional area $2\pi a\delta$, where a is the radius of the conductor. The AC resistance of the conductor is given by:

$$R_{ac} = \frac{\rho}{2\pi a\delta} \text{ ohms per centimeter} \qquad (11\text{-}3)$$

Where:

ρ = the resistivity of the material in ohm-centimeters
a = the radius of the conductor in centimeters and
δ = the skin depth in centimeters

Figure 11-1A illustrates the handicap imposed by skin effect for representative sizes of copper wire in the 1 to 1000 megahertz region of the spectrum. Skin depth and the ratio of AC resistance to DC resistance is plotted.

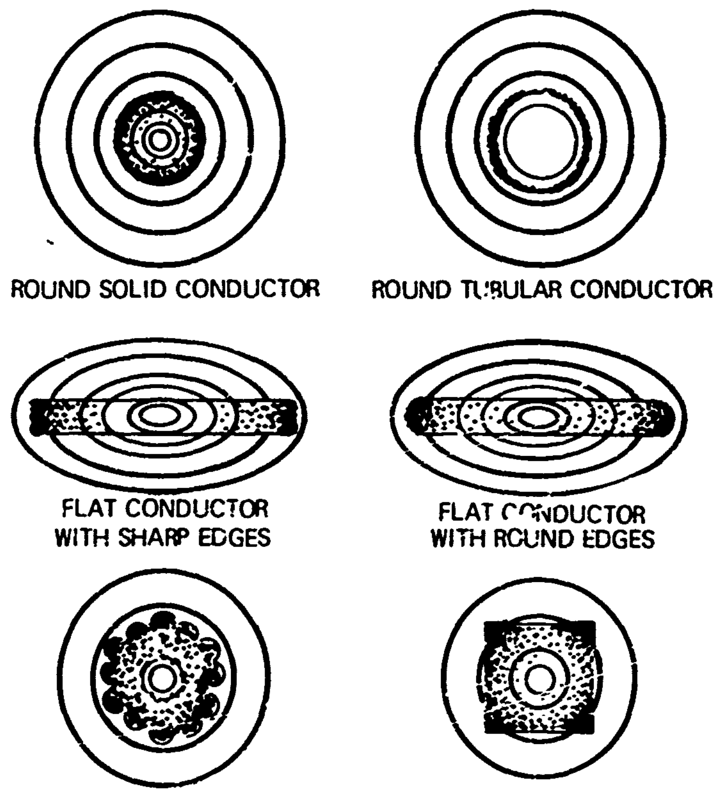


FIGURE 11-1 FLUX LINES AND CURRENT DISTRIBUTION IN VARIOUS CONDUCTOR CROSS-SECTIONS AT A HIGH FREQUENCY SHOWING HOW SKIN EFFECT CAUSES THE CURRENT TO CONCENTRATE AT THE EDGES. (THE DENSITY OF THE DOTS INDICATES CURRENT DENSITY.)

It is significant that the largest wire size has the largest ratio of AC to DC resistance. This does not indicate that small conductors are better than large ones for AC current, but rather that at high frequencies large round solid conductors are an inefficient use of copper.

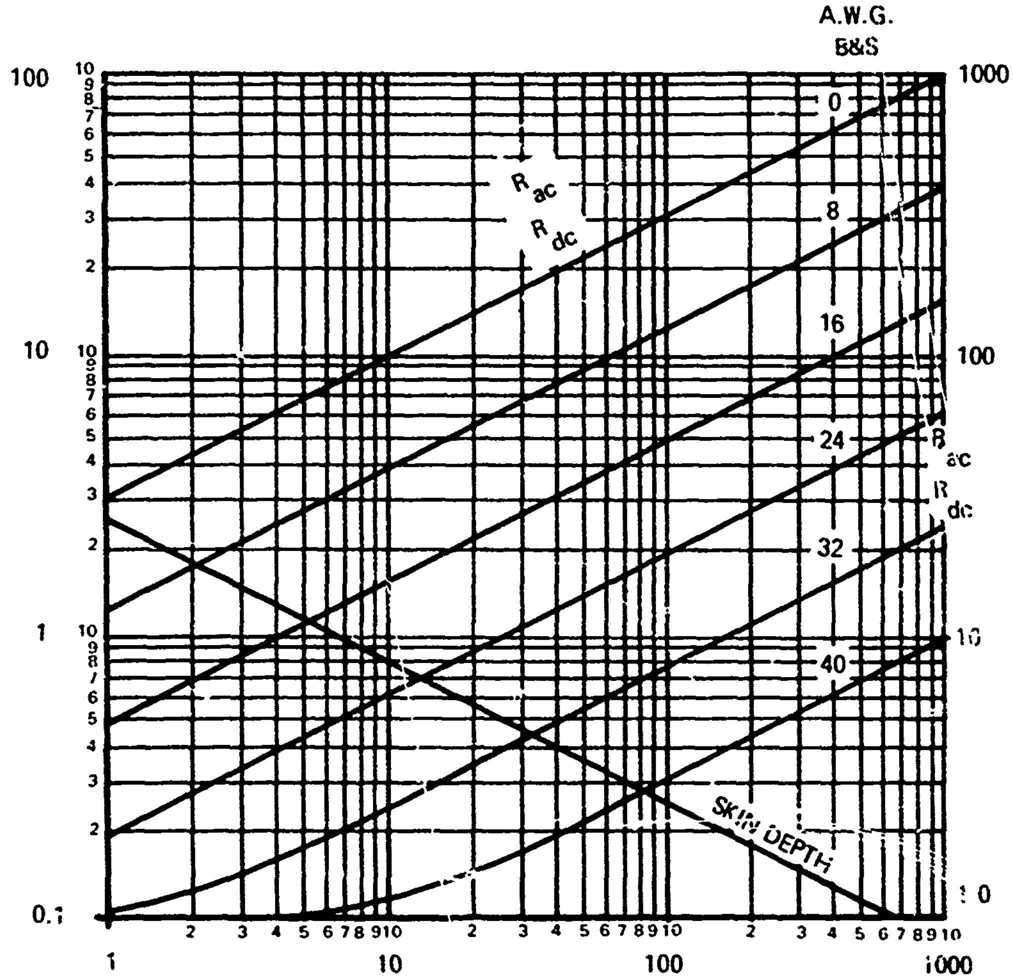


FIGURE 11-1A SKIN DEPTH AND RESISTANCE RATIOS DUE TO SKIN EFFECT COPPER WIRE

When two or more wires are close to one another, the effective AC resistance can be further increased by the proximity effect. Figure 11-2 illustrates the proximity effect in two conductors with current in the same direction and with current in opposing direction. When the current is in the same direction in the conductors, the current density increases away from the

proximate surfaces, and when the currents are flowing in opposite directions, the current density tends to concentrate at the near surfaces.

Stranded conductors consist of a number of strands in close proximity to one another. The strands are twisted about each other to keep the individual strands in position and add flexibility to the conductor. At higher frequencies, the proximity of the strands to each other forces the desired current to the surface of the outer strands, causing skin effect. Since the strands are twisted, causing the individual outer strands to form a helix, coupling between turns is increased, thereby increasing the series self-inductance of the conductor. In addition to the higher self-inductance of a stranded type conductor, skin effect increases the AC resistance of the conductor. Stranded conductors are useful up to 1200 Hertz. Above this frequency, it is recommended that stranded conductors not be used. The concentration of current near the surface of the outer strands acts in the same way as skin effect to raise the AC resistance of the conductors. At 60 Hertz, two closely spaced parallel conductors carrying current in the same direction will carry 130 percent of the current of a single conductor under the same conditions instead of the expected 200 percent. Three conductors will provide just 160 percent increase in current at 60 Hertz instead of 300 percent. This effect decreases as the distance between the conductors increases.

FIGURE 11-2 PROXIMITY EFFECT OF CURRENT IN TWO PARALLEL WIRES

Solid round conductors have lower self-inductance per unit length and lower AC resistance than do stranded conductors. For medium and low currents, a round cross-section is the most efficient conductor. However, to carry large currents safely a large conductive cross-sectional area is required, and solid wire of greater than 1/4 inch in diameter is commercially difficult to obtain. Therefore, a flat conductor such as bus bar of sufficient cross-sectional area to handle the required current is commonly used.

Flat conductors that have sharp edges will cause electric energy to concentrate at these edges as frequency increases. Figure 11-1 shows the current in the flat conductor traveling in two parallel, but almost separate, paths. Because of the phase displacement, the flat conductor becomes an efficient stub antenna. If the edges are rounded so that the flat conductor becomes elliptical, the currents will be more evenly distributed throughout the conductor, reducing the possibility of phase displacement and thereby reducing the antenna efficiency.

The best compromise for commercial availability, cost, weight, cross-sectional area, skin effect and AC-to-DC resistance ratio is the tubular conductor. Over-all self-inductance is reduced by the absence of a conductive medium in the center. For higher frequencies, the effective series resistance and series self-inductance per unit weight of material and per unit length will be less in the tubular conductor than in one of any other shape.

A ground plane is the mechanism by which a number of electrical or electronic units are maintained at the same electrical potential so that electrical interference is not coupled from one to the other. An ideal ground plane would be an equipotential plane; however, all conductive materials have some impedance that contributes a potential difference when current flows through them. The ground plane can be a flat conductive area, or wires or tubular conductors that interconnect enclosures or chassis to essentially the same reference potential. The physical configuration and the conductivity of the material will determine the intrinsic impedance of the ground plane. Other factors such as contact area, contact pressure, current flow due to potential differences between the interfaced units, current distribution, and overall dimensions in wavelengths will determine the performance of the ground plane.

Many system descriptions use terms such as ground point, single reference point, and vehicle ground point, but, because all system components are connected to a ground point and must therefore be referenced to the same potential, the connecting network forms a ground plane. Because no conductor has zero impedance, a potential can exist between the system components and the ground plane, and current flowing in the ground plane conductors will radiate energy. A useful rule of thumb that was empirically derived suggests that the largest dimension of the ground plane (L_{MAX}) be less than $\lambda/15$ or, in terms of frequency, in megahertz.

$$f_{MHz} < \frac{20}{L_{MAX}} \quad \text{(feet)} \tag{11-4}$$

This rule for the critical dimensions of the ground plane applies to another possible source of interference.

Electrical energy used to power electrical and electronic devices in military aircraft is usually either 28 volts DC or 115 volts AC of 400 Hz to 1600 Hz. Distribution of this power by wiring creates magnetic-induction fields unless the circuits are balanced. The physical configuration of the ground plane, the conductivity of the ground plane, the permeability of the conductive material, the frequency, and the flux density of the induction field will determine the magnitude of the circulating currents induced into the ground plane by the varying magnetic flux.

APPLICATION TO AVIONIC WEAPON SYSTEMS

All electrical systems, other than the most simple, require a unique system of reference interconnections. Design of the system will be based on economics, complexity of the system, and environment of the system. To design the ground

reference system, tradeoffs will have to be made. Practical ground systems are neither pure single point reference systems nor multiple point reference systems. A single point ground system is only a concept and cannot be achieved in practice. Modern systems use several separate ground planes to avoid interference between various system functions. For instance, separate ground planes in each subsystem for structural grounds, signal grounds, shield grounds, and AC prime and secondary power grounds would be desirable. These individual ground planes are finally connected by the shortest route back to the system ground point where they form the overall system ground plane.

Grounding philosophy should be a function of unit, subsystem, or system frequency spectrum susceptibility, separation between units, subsystems, and systems, the dimensions of the ground plane used for the ground reference, the induction field ambient levels, the length (in terms of wavelength) of the connection to the ground plane, and the configuration of the conductor used to reference the electrical or electronic unit to the ground plane. It is not enough to base the grounding system on fundamental frequencies alone; the spurious generation capabilities of the electrical and electronic equipment will have to be considered. Multiple grounding or referencing to ground will be necessary to limit the radiation of undesired signals.

To minimize the potential differences between the parts of the system, the various equipments are grouped by their characteristics, and each group has its own separate ground system as indicated in the following paragraphs.

Static and Structural Ground

Structural grounds are conductive parts of a system that includes mechanical strength members, mechanical parts, enclosures, static shields, cable shields, black boxes, and junction boxes. Each of these items is grounded to the structural ground at only one point.

Connections of static or low frequency cable shields to the ground system should be routed through the pins of any connectors encountered. If a cable shield appears between two static shields (for the low frequency case), it is generally advisable to connect the cable shield to one of the static shields, but not to both. The other end of the cable can be left floating, if the cable is less than $\lambda/15$ in length. The combined shields and the remaining static shield are each connected separately to the structural ground.

Shields enclosing high frequency circuits and cables must be designed to ensure that all openings, covers, and connectors are RF tight. High frequency circuits are defined as circuits containing a maximum frequency (in megahertz) of:

$$f_{MHz} > \frac{20}{L_{MAX}} \qquad (11\text{-}5)$$

where:

L_{MAX} = the maximum circuit dimension in feet.

High frequency shields are grounded to the static ground at least at both ends and preferably also at intervals, depending on the frequencies being shielded. When high and low frequencies are present, a compromise can be reached by connecting one end directly to the ground system and the other end through an appropriate capacitor, according to the high and low frequencies present, to the static ground system, using the relationship:

$$X_{cl} = \frac{f_h}{f_L} X_{ch} \qquad (11\text{-}6)$$

wherein:

f_h = the lowest of the high frequencies that require multiple-point grounding.

f_L = the highest of the low frequencies that require single-point grounding.

X_{ch} = the maximum impedance between shield and ground that f_h can see to still be effectively multiple-point grounded.

X_{cl} = the minimum impedance between shield and ground that f_L must see to preserve single-point grounding at that frequency.

Primary AC Power Ground

Aboard an aircraft, primary power is generated by the engine-driven generator(s) and the neutral is referenced to the vehicle structure.

Any secondary AC power that is derived but separated from the primary AC power, has its own ground system with the ground returned to the secondary power source. At the power source, the secondary power ground system is then referenced to the vehicle structure.

The grounding arrangement for primary and secondary power is shown in Figure 11-2A. Each load is also grounded to the structure.

DC Power Ground, Signal Ground, or Circuit Ground

DC power is supplied to circuitry that uses a variety of frequencies, from DC up into the GHz range, so that the DC ground is usually the most complicated of the system grounds. There are a number of special cases in which a DC supply cannot be grounded at all, but in general, the DC return of every DC power supply should be connected by a separate wire at one point to the system ground point.

Seldom can an ideal grounding scheme be achieved, but the designer should strive for the most advantageous pattern. The following ground rules may help.

a. Supply low frequency and high frequency circuitry from separate DC supplies or regulators.

b. Supply low-signal-level and high-signal-level circuitry from separate DC supplies.

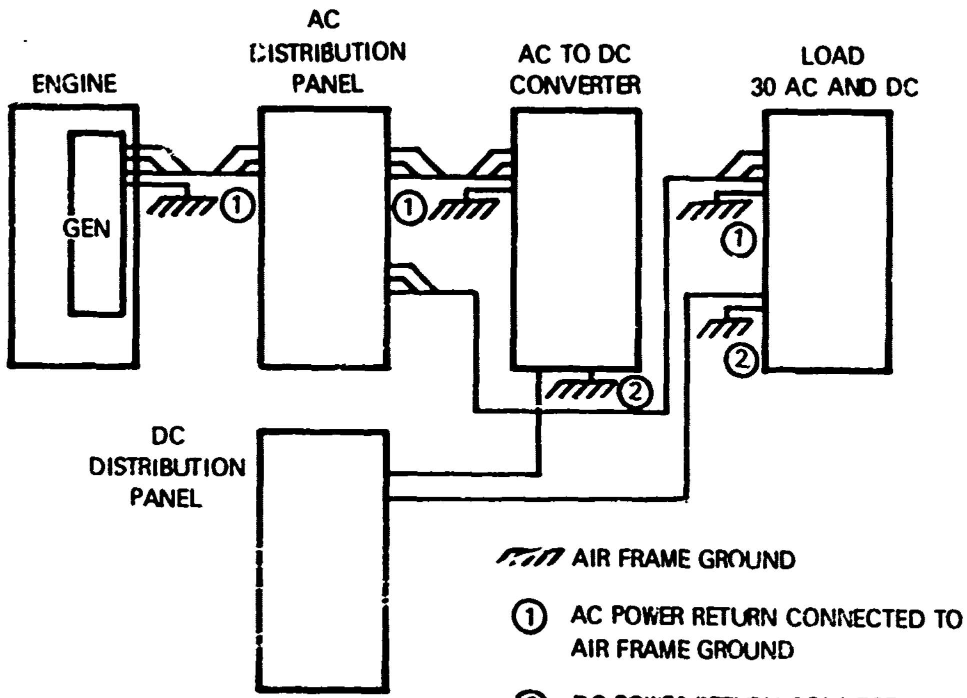


FIGURE 11-2A PRIMARY AND SECONDARY POWER GROUND

c. Connect the DC ground to the DC power ground of its own supply, and only of its own supply.

d. Connect the DC power ground at one point to the system ground point or ground plane.

e. Where several power supplies of different DC potentials must share a common DC power ground, interconnect the zero-volt terminals of each supply and make a single-point connection to the system ground point.

f. Run separate grounds to the DC power ground from each module or critical stage. In some cases, several non-critical modules containing functionally similar circuitry can have a common ground lead to DC power ground. Engineering judgment must determine the degree of application of these rules.

g. For RF circuits, the circuit parts and interconnecting wiring are often mounted on and close to a ground plane formed by a copper sheet and grounded directly to the system ground plane.

h. When coaxial cable is used for signal transmission in high frequency circuitry, the outer conductor is connected to chassis grounds at both ends. If both circuits are also separately grounded to their DC power grounds or returns as shown in Figure 11-3, a ground loop is formed into which low frequency current can be induced by magnetic flux linkages from an outside source. In many cases, this may not affect the high frequency circuitry but the loop can transmit the low frequency energy to another susceptible circuit. As a first step,

the loop may be opened by inserting a series capacitor at one end to increase its low frequency impedance. One of the ground returns might not be necessary. Or the loop area may be reduced by running ground leads close together and shielding them. In this context, triaxial cable has an advantage over coaxial cable because it allows the use of the outer conductor as a shield that is multiple-point-grounded to the system ground plane, thereby forming a shielded tunnel for the coax. The induced current flowing around the group loop depends on the loop area, the magnetic flux linking the loop, and loop series impendance.

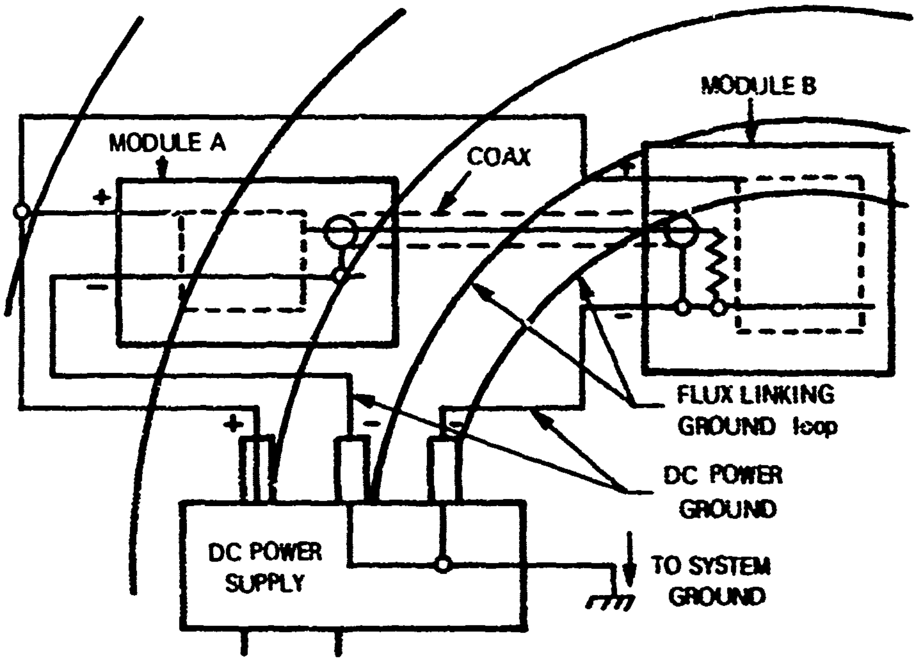


FIGURE 11-3 FLUX LINKING A GROUND LOOP

An often effective method to reduce the flow of circulating current in a ground loop is to isolate one or more of the circuit ground connections by inserting a resistance between the circuit ground and its DC power ground connection. If some signal gain can be spared, a resistive coupling can at times be inserted between the coax outer conductor and ground. In certain cases, AC coupling, especially frequency-selective AC coupling, has been successful.

i. Often standard cable assemblies that contain multiple conductors include some conductors that are not used. To prevent the spare conductors from acting as EMI coupling media, they should be single-point-grounded with half of the spare conductors grounded at one end and the remaining half of the spare conductors grounded at the opposite end. When these spare conductors are grounded in this way, they not only are prevented from acting as EMI coupling probes, but they will function as effective electrostatic (Faraday) shields within the cable assembly, thereby isolating adjacent signal circuit conductors and reducing cross-talk due to capacitive coupling.

Shield Grounding

The method of terminating a shield to a ground plane will determine the shielding effectiveness. As frequency increases, current flow is concentrated closer to the surface of the conductor. Thus, complete peripheral grounding of a shield will produce the most effective connection of a shield. The braid that commonly serves as a cable shield acts as an effective barrier to low frequency electric fields, but at shorter wavelengths, it becomes also effective for the electromagnetic field. The distributed capacitance between the conductor and the shield will couple some energy to the shield. The shield, in absorbing the radio frequency energy, will develop an induced current. When the shield is connected to a ground plane through a minimum impedance, no appreciable potential can develop and it will not radiate radio frequency energy.

The coaxial cable, though multiple grounded to the DC power or signal ground, will still have the return signal current flowing through the shield except at very low frequencies of less than one kHz. However, it is sometimes inconvenient to ground a shield often enough to keep radiation from a coaxial cable shield. In such cases, a double-shielded cable, where the two shields are electrically independent of each other, will provide the additional attenuation required for electromagnetic compatibility. To fully realize the shielding capabilities of both shields, terminate the shields to the ground plane independently and not through a common connection. By independently connecting each shield to the ground plane, up to a 30 dB improvement can be obtained. An additional 10 to 12 dB improvement can be realized by independently terminating each shield to independent ground planes, such as the inner shield to the signal ground and the outer shield to the static ground. Connectors are available that allow independent peripheral grounding of each shield, thus affording maximum EMI protection at radio frequencies. This technique is of particular importance when conducting high-power radio frequency energy obtainable from present day communications and data transmission links and reducing the fields about the conducting cables.

Electroexplosive Devices

Many aircraft and aerospace systems make extensive use of electroexplosive devices (EEDs). An EED is an electric initiator or other component in which electrical energy is used to detonate an explosive contained within the device. Because electrical energy is used to set off the device, EEDs must be protected from accidental ignition by environmental electromagnetic fields.

When EEDs are used, the basic design of the system should consider the coupling of RF energy from environmental electromagnetic fields into EEDs. This coupling is reduced by shielding all susceptible parts of the EED, including the actuator circuits. For shielding to be effective, proper grounding techniques must be used (Figure 11-2). All grounds must be made with bonds meeting the requirements for Class R bonding in accordance with MIL-B-5087, *Bonding, Electrical and Lightning Protection for Aerospace Systems.*

The requirements for the use of EEDs in weapons systems are given in Mil-P-24014 (WEP), Preclusion of Hazards from Electromagnetic Radiation to Ordnance, General Requirements For.

BONDING

THEORY OF BONDING

Electrical bonding mechanically connects metal parts so that low impedance electrical contact is made between system components or structural members. Proper electrical bonding is required to reduce potential gradients in the ground system. In radio interference suppression, bonding influences the performance of filters and shields because it acts to prevent the formation of RF potentials and static charges. In aircraft, bonding will provide a low impedance path for all equipment using the airframe as a return circuit.

Figure 11-4 shows two solid bars of a high conductivity material such as copper. If the bars are brought together, a current path through the bars is formed, but a special situation will exist at the point of contact. The resistance there will be different from that encountered elsewhere in the bar. The resistance R of a conductor of length l and cross-section A is given by:

$$R = \rho \frac{l}{A} \qquad (11\text{-}7)$$

where ρ is the specific resistivity and is a property of the conductor material and temperature. The current that passes through the bar is a function of the applied voltage and the resistance. At the point of contact of the two bars there is a change, ΔR, in the resistance because of a number of factors. These factors include the degree of contact of the two bar faces and the condition of the surfaces that are joined. If perfect contact of ideal surfaces could be made, ΔR would reduce in value to zero and the problem of electrical connections would disappear. It is the need to make ΔR approach zero that makes bonding an

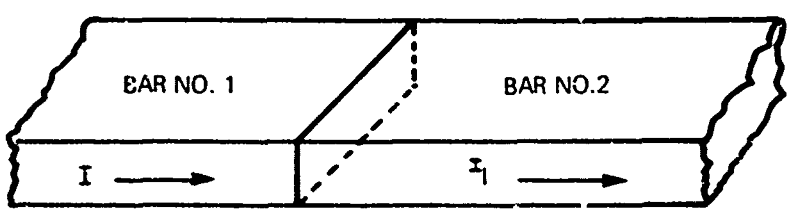


FIGURE 11-4 CURRENT MOVEMENT IN CONDUCTING MATERIALS

important consideration. Bonding is defined as making a fixed union between two metallic conductors to provide an acceptably low resistance to a current passing through it. This fixed union can be accomplished by a variety of methods, each of which has the same objective: to obtain a minimum ΔR. These techniques vary widely depending on how great a ΔR will be acceptable.

For reducing electromagnetic interference, the method that makes the joint a homogeneous mass of the joined metals is the best. This may be done by welding or brazing. Useful but of lesser value are methods that make extremely good physical contact, such as soldering and pressure connections.

Proper bonding will provide electrical homogeneity to shielded enclosures and will prevent the development of potential differences on conducting equipment frames, as well as on enclosures and cables. Such bonding will protect persons who may come in contact with electronic equipment from shock, and it will also minimize the accumulation of static charge buildup which, on being discharged, produces broadband interference. Good bonding depends upon the degree of contact and the condition of the surfaces that are joined.

A high degree of contact means that the surfaces to be joined are perfectly plane and clean with no surface irregularities. This can occur only if the surface has been accurately machined, highly polished, and carefully cleaned. If pressure is used to overcome the difficulty of contact, the degree of contact (even with great pressure) is limited by surface irregularities, hardness of the material, and toughness of the oxides or contaminants. Pressure contact is effective only with a good surface and with great effort to maintain the quality of the surface until installation. If pressure contact bonds are made, then devices that "bite" into the conductors to be joined are the most effective. The condition of the surfaces to be joined is of such vast importance that it in itself represents a complex field of specializtion.

Types and Classes of Bonds

Bonds can be classified according to several different criteria. A bond can be described as a permanent or semipermanent bond, or as a direct or indirect bond. It can also be classified according to the intended use. Bonds classified according to application are described in MIL-B-5087B.

Permanent bonds are just what the name implies. The interface between the two units to be joined is cleaned and then made permanent and waterproof by welding, brazing, sweating, or other metal flow processes The impedance across the joint is primarily resistive in nature. A permanent bond virtually eliminates movement and resultant resistance variations between the two surfaces.

Sometimes bonded surfaces must be disconnected occasionally for such things as inspection or replacement of parts. Such bonds are semipermanent bonds. Semipermanent bonds include those made by metal-to-metal joints held together by threaded locking devices, riveted joints, tie-rods, pinned fittings driven tight, and clamped fittings normally permanent and immovable after all insulating finishes are removed from the contact area. The term "lock-threaded devices" does not mean that bonding may be done by means of screw threads alone. The use of self-tapping screws for bonding purposes is expressly prohibited. A direct bond is one in which two units are joined by direct metal-to-metal contact. This contact can be held by methods making it either a permanent or semipermanent bond. A direct bond is much preferred to an indirect bond and a direct bond that is also permanent is best whenever practical.

An indirect bond is one in which the electrical contact between the two units is made through an intermediate conductor such as a jumper or bonding strap. Indirect bonding should be used only when direct bonding is impractical. The principal reason for this is that a bonding strap or jumper can exhibit appreciable impedance when subjected to RF potentials. The bonding jumper can be attached to the units by methods making it either a permanent or semipermanent bond.

Bonding Characteristics, Applications, and Tests

The primary characteristic of all good bonds is that they provide a low impedance path between two units. A bond must be made so that it will retain this low impedance throughout the life of the joint.

Both direct and indirect bonds are subject to chemical corrosion. This corrosion must be taken into account when a bond is made, to assure a low impedance for the life of the joint. Chemical corrosion is due to galvanic action, electrolysis, or both.

Galvanic corrosion depends on the moisture between the two contacting metal surfaces. Where there is enough moisture, the two contact surfaces behave like electrodes in a chemical wet-cell battery When a metal is placed in contact with water, some of the metal goes into solution as positively charged ions of the metal, leaving a surplus of negative ions on the metal surface. When two metals are joined, this process occurs at the surface of both metals, and the rate at which the ions go into solution is a property of the metals. If the metals are the same chemically, no potential difference occurs because positive ions develop at the same rate and there is no migration of ions from one surface to another. The worst effect will be that the metal surfaces will eventually wear away, but such a process is quite slow and of no great importance; therefore no galvanic action is considered to occur. But if the metals are different chemically, the difference in rates at which the metals release positive ions causes a potential difference to be developed between the two metals.

The tendency of metals to go into solution as ions is based on their property of electrochemical force. Table 11-1 gives the electrochemical series for selected metals. The chemical action represented by the table indicates that metals higher in the series (the ones with the lower numbers in the table) lose positive ions to the metals below them. The higher metal corrodes by the loss of metal, while the other metal does not. This leads to a very important consideration in bonding; that is, parts of a bond that cannot be replaced should be made of a metal lower in the series than the adjoining metal. The further apart the metals are on the series, the greater the galvanic action, with correspondingly greater corrosion. For example, there will be more galvanic action from magnesium to aluminum than from magnesium to zinc. Because of the described phenomena, metals for bonding should be close together in the electrochemical series.

Electrolysis also causes bonds to corrode by chemical action. Electrolysis occurs if DC current flows between two metals in contact with a conducting

1. Magnesium	12. Nickel
2. Magnesium alloys	13. Brass
3. Zinc	14. Copper
4. Aluminum 25	15. Bronze
5. Cadmium	16. Copper-nickel alloys
6. Steel or iron	17. Monel
7. Cast iron	18. Silver solder
8. 18-8 stainless steel	19. Silver
9. Lead-tin solders	20. Graphite
10. Lead	21. Gold
11. Tin	22. Platinum

TABLE 11-1 ELECTROCHEMICAL SERIES FOR SELECTED METALS
(Listed in decreasing order of tendency to go into solution at ions.)

solution. It does not depend on the chemical composition of the metals involved, but principally on the conducting solution and the available DC current. The conducting solution can be the ambient moisture of a slightly acid concentration, and because substantial DC currents can flow in the ground system, electrolytic action can readily occur. The chemical action will cause rapid corrosion and eventual destruction of the bonding joint. When making a joint between two dissimilar metals, the relative areas of the potential anode and cathode should be considered. A larger cathode area will produce greater corrosion at the anode due to a greater electron flow, which is the result of a larger source of supply. A reduction in cathode area reduces the source of supply, thereby lowering the amount of corrosion of the anode (Figure 11-5).

The use of bonding jumpers in direct bonding presents problems in maintaining low impedance paths. At low frequencies, bonding jumpers do not present any special problems except for resistance, and wire or length of copper braid can be used. At higher frequencies, however, the impedance becomes a critical design consideration. A bonding jumper has the usual electrical parameters of R, L, and C; of these parameters R is an inherent property of the jumper resistivity depending on the material selected; C is dependent upon the physical configuration and separation between the bonded units; and L is dependent upon the physical dimensions of the bonding jumper. For a straight bonding strap of nonmagnetic metal L is given by:

$$L\,(\mu H) = 0.00508a\left[2.303\log_{10}\left(\frac{2a}{b+c}\right) + 0.5 + 0.2235\left(\frac{b+c}{a}\right)\right] \quad (11\text{-}8)$$

and for a wire of circular cross section

$$L\,(\mu H) = 0.00508a\left[2.303\log_{10}\left(\frac{4a}{d}\right) - 0.75\right]$$

where:

a = the length of the strap in inches
b = the width of the strap in inches
c = the thickness of the strap in inches and
d = the wire diameter in inches

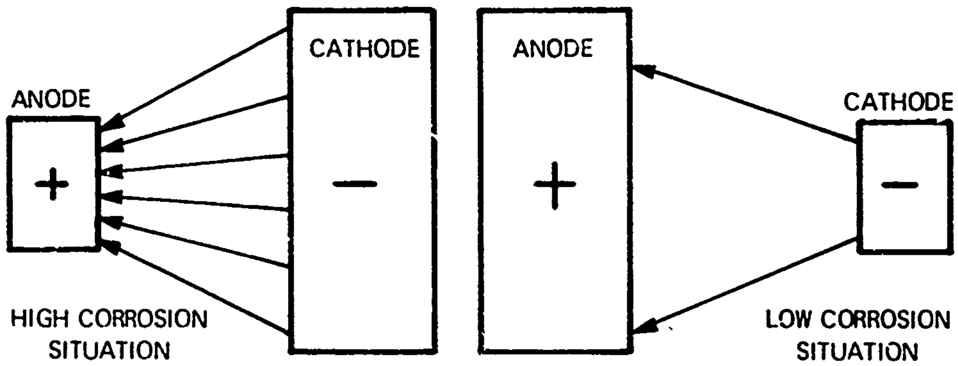


FIGURE 11-5 EFFECT OF RELATIVE CATHODE ON RATE OF CORROSION

The inductive reactance variation with frequency for several types of bond jumpers leads is shown in Figure 11-5A. Lengths of 0.1, 1, 10, and 100 inches have been selected. An interpolation can be made between these values for estimating purposes. Other factors such as RF resistance and shunt capacity are included in the total impedance of a bond jumper. An equivalent circuit for the bonding strap is shown in Figure 11-6.

Not considering R, the equation for the impedance Z of the equivalent circuit is given by:

$$Z = \frac{\omega L}{1 - \omega^2 LC} \quad (11\text{-}9)$$

where:

ω is the angular frequency ($2\pi f$)
C is the capacity in Farads, and
L is the inductance in Henries

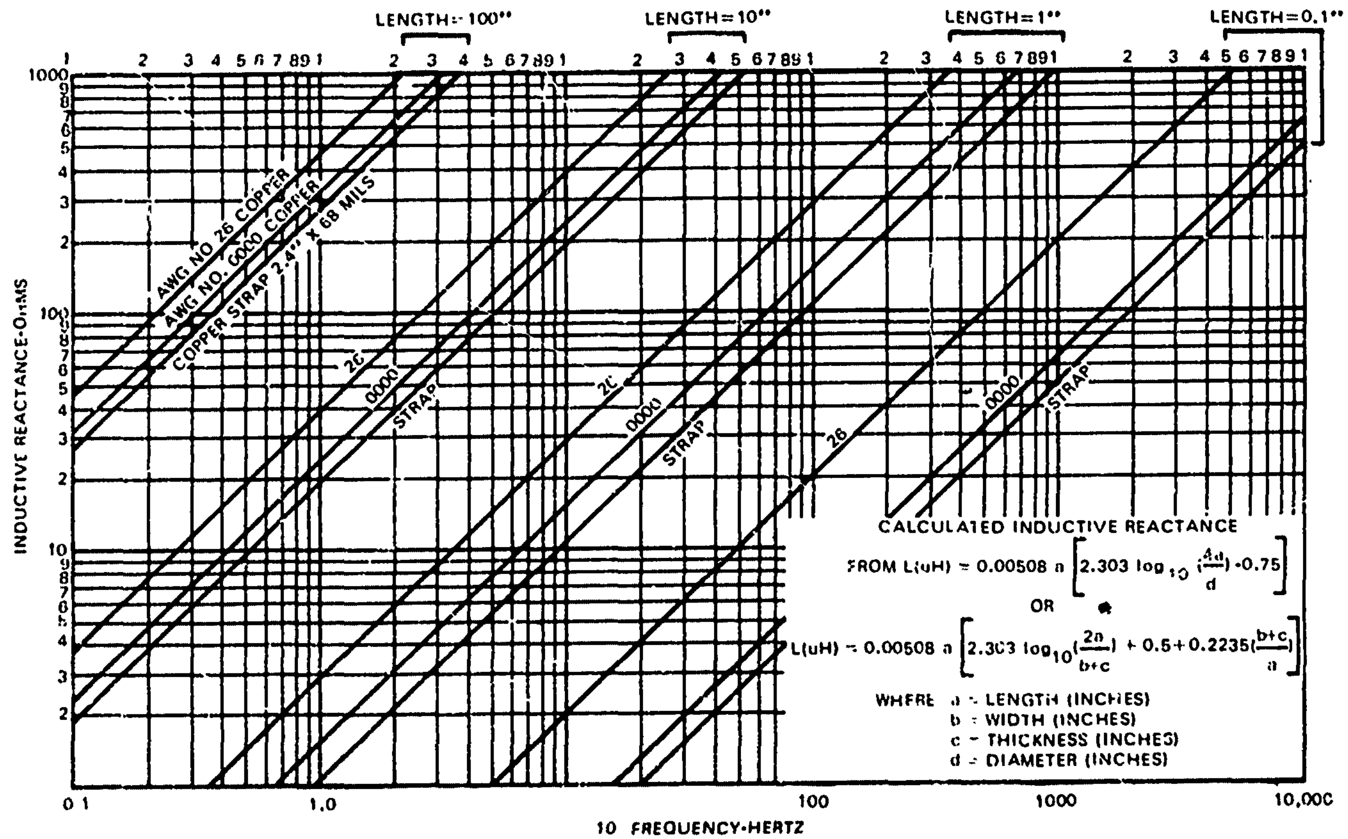


FIGURE 11-5A INDUCTIVE REACTANCE OF WIRE AND STRAP BOND JUMPERS

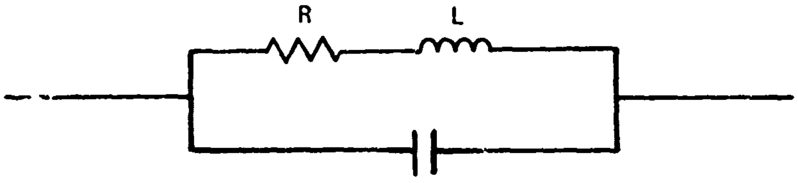
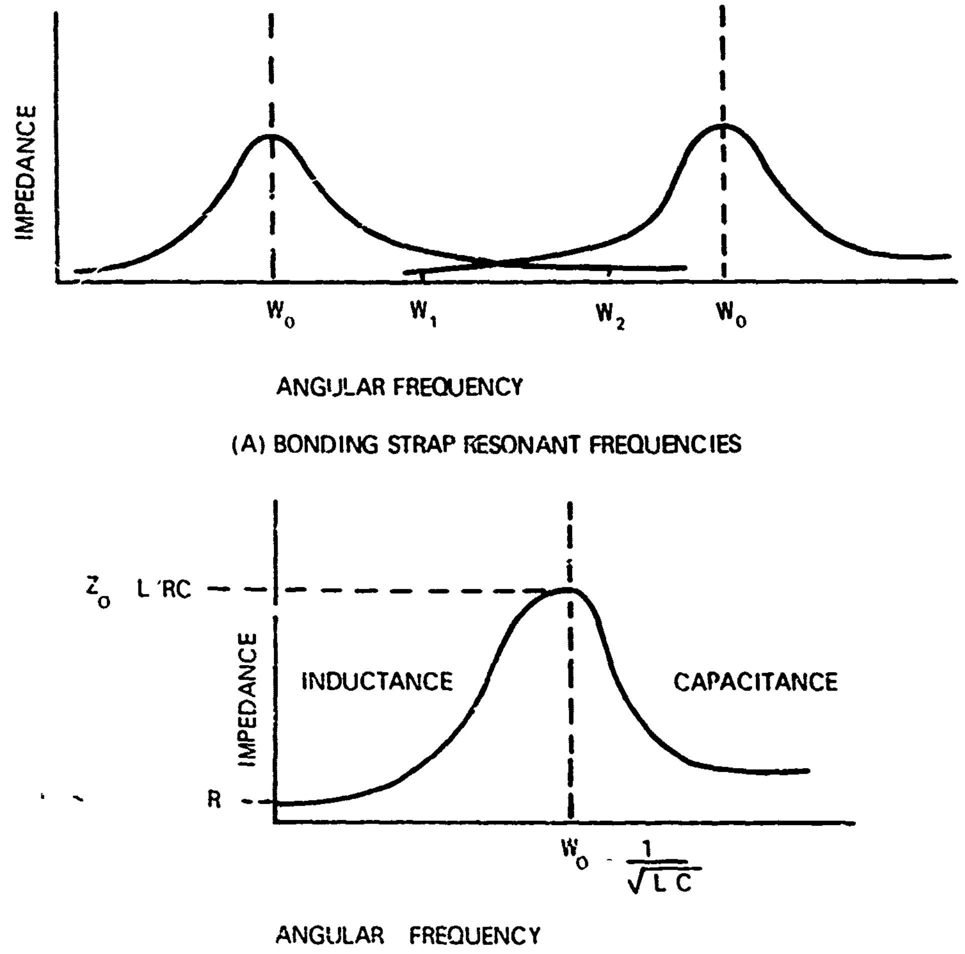


FIGURE 11-6 EQUIVALENT CIRCUIT OF A BONDING STRAP

If $\omega^2 LC$ is less than one, the bonding strap appears principally as an inductance. As $\omega^2 LC$ approaches one, the magnitude of the impedance increases, and as $\omega^2 LC$ goes above one and continues to increase, the bonding strap appears to be principally capacitive (Figure 11-7b).



(A) BONDING STRAP RESONANT FREQUENCIES

(B) IMPEDANCE OF A BONDING STRAP

FIGURE 11-7 BONDING STRAP RESONANCE

Consequently, to keep the impedance of the bonding strap low, the values of L and C must be such that the value of $\omega^2 LC$ remains as far as possible from 1, that is, the resonant frequency of the bonding strap should be kept as far as possible from the EMI frequencies of concern. In theory, the resonant point of the bond could be above or below the EMI frequencies encountered (Figure 11-7a). However, only the high resonant frequency is considered because of the large values of L and C required at the low resonant frequency.

The physical size of the bonding strap affects the RF impedance. The impedance of a strap increases linearly with its length and decreases exponentially as its cross-sectional area increases. Because of this, bonding straps must maintain a length to width ratio of not more than 5 to 1, with a preferable design ratio of 3 to 1, and a minimum thickness of 0.0025 inch.

Direct current resistance measurements of a bond and the impedance measurement at RF frequencies of the same bond cannot be directly correlated. In general, the direct current resistance alone cannot be used as a measure of effectiveness of the bonding. Bonding impedance between two members can be measured with an admittance bridge or by the insertion-loss method in accord with MIL-STD-220. Resistance measurements can be used in accord with conventional techniques.

A comparison can be made between the DC resistance measurement technique and the RF impedance method of evaluating bonding connections. A number of techniques have been advanced for making bond impedance measurements, and specifications such as MIL-B-5087B state that limited resistance measurements must be made as partial proof of satisfactory bonding. These resistance measurements are only to verify the existence of the bond and are not to be considered as final proof that the bonding is satisfactory. In fact, none of the various tests, whether resistance or impedance tests, will ever prove that the bonding is satisfactory. Such proof can only be developed by a more comprehensive and exhaustive test.

Impedance measurement techniques are limited at upper frequency ranges because of the errors introduced as a result of standing waves. No matter which technique is under consideration, the test lead contact impedance and the bonding impedance that is to be measured must be separated. If an admittance bridge with separate current and potential probes is used, it overcomes this problem of separation at low frequencies because standing waves are not a problem at these frequencies. Slotted waveguides and associated equipment are effective for bond impedance measurements in the microwave frequency band. The major difficulty with such a bond impedance measurement is that under normal field conditions, it is an extremely difficult technique to use.

At present, techniques for measuring bonds that are given in the various specifications are the only ones available, and their use is limited. A great deal more research and development on measuring impedance of bonds will be required. The objective will be to develop more reliable measurement criteria so that bonding measurements can be used to assess the reduction of potentials in a system. Development work is presently in progress to improve impedance measurements, particularly in the microwave frequency band. The feasibility of

using the thermocouple action of micropotentiometers is being investigated. In the RF range, more sophisticated measurement techniques are being developed, but in this frequency range, standing waves on the test probes become a problem and make the measurements inaccurate.

Accordingly, in the higher frequency range, the most practical approach to assure the effectiveness and quality of the bonding installation is: to measure DC resistance of bonds as required in the specifications; to assure that the bonds comply within their limitations; and to depend on careful adherence to technical rules and to principles of cleanliness and good workmanship in making the bond. Inspection of the bonds will probably give more assurance of good bonds than will a bonafide bond-testing program Bonding tests are not yet accurate enough to be depended upon, and practically, they are quite costly and difficult to conduct. It is necessary to depend on system tests to assure that good bonding design prevails.

REVIEW OF MIL-B-5087B

MIL-B-5087B, (ASG), October 1964, *Bonding, Electrical and Lightning Protection, for Aerospace Systems* is the principal document concerning bonding. The specification sets forth requirements and tests to ensure that the structures of aerospace systems are electrically stable and free from such hazards as lightning, static discharge, and electrical shock, and provides for the suppression of electromagnetic interference resulting from these hazards.

The materials used in making a bond are important. Metals react differently depending upon the environment and the metals with which they are in contact. For this reason, data is given to be used in selecting the hardware for a particular bonding purpose.

MIL-B-5087B divides bonds into classes according to the application of the bond. Each class of application has its own requirements which must be met. If a bond is used for two or more applications, it must conform to the most critical requirement. Following is a summary of the requirements for each class:

Class A (antenna)

All radiating elements must be provided with a ground plane of negligible impedance in the frequency ranges involved and must be of adequate dimensions not to detract from the desired antenna radiation patterns. This requirement excludes equipment such as radar scanners in which the ground plane is part of the equipment.

Antennas that depend upon low resistance for efficient operation must have a bond installed that will provide a low impedance path of minimum length to the appropriate metal portion of the antenna for the RF currents flowing on the surface of the aircraft.

Class C (current return path)

When a bond is part of the current return path, the bond must be able to

carry the current load without an excessive voltage drop. The specification includes tables that give the current-carrying capacity of wire or cable sizes and maximum allowable voltage drop between the load and the point of regulation for different system voltages.

Class H (shock hazard)

Metal conduit that is carrying electrical wiring and the exposed conducting frames or parts of electrical or electronic equipment must have a low-resistance bond of less than 0.1 ohm to the structure. Metal conduit is to be bonded to structure at the termination points and at the break points. If the equipment contains a ground terminal that is internally connected to exposed parts, this terminal must be connected to ground.

Class L (lightning protection)

Requirements for Class L bonds are designed to permit an aircraft to carry the current produced when it is struck by lightning without risk of damaging flight controls or producing spark or voltages greater than 500 volts. The requirements are based on a lightning discharge with a current waveform of 200,000 amperes peak, a width of 5 to 10 microseconds at the 90-percent point, not less than 20 microseconds width at the 50-percent point, and a rate of rise of at least 100,000 amperes per microsecond.

Individual bonding jumpers for lightning protection must be not less than No. 12 AWG for tinned stranded copper wire or No. 10 AWG for stranded aluminum wire. These wire sizes are valid only when a minimum of two jumpers are installed to carry the lightning current and when the jumpers are not subject to direct arc. When the jumpers are subject to direct arcing, substantially larger wire sizes, 40,000 circular mils (AWG No. 4) minimum, are required for protection against multiple strokes. Solder connections are not allowable in jumpers that carry lightning currents. The method of attaching terminals to jumpers must be verified by test.

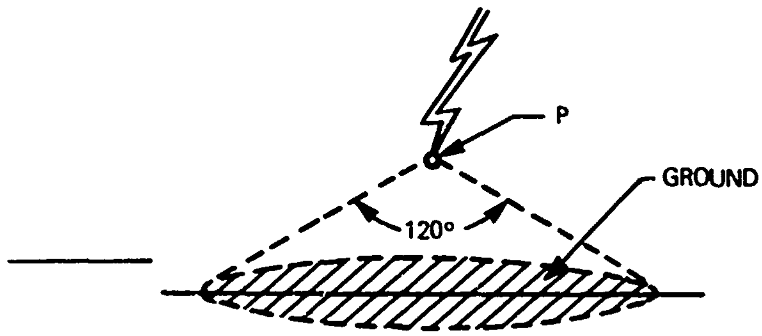
Control surfaces and flaps must be bonded across the hinges with a bond at each hinge and not fewer than two bond jumpers. Additional jumpers must be used where necessary to protect control cables and levers. The length of the discharge path through the control system must be at least 10 times the length of the path through the jumpers. A piano-type hinge can be considered adequately bonded if the resistance through the hinge is less than 0.01 ohm.

All external electrically-isolated conducting objects, excluding antennas that protrude above the vehicle skin, must be bonded to the skin or structure. Large nonconducting projections essential to flight or which house personnel must have a lightning path distributed externally over the exposed area leading to the vehicle skin. This conductive path cannot affect the structural integrity of the projection. These requirements are superseded by vehicle flight safety, flight characteristics, crew visibility, and equipment performance. All conducting objects inside these projections must be within the protective zones formed by the conductive paths according to MIL-B-5087B (Figure 11-8)

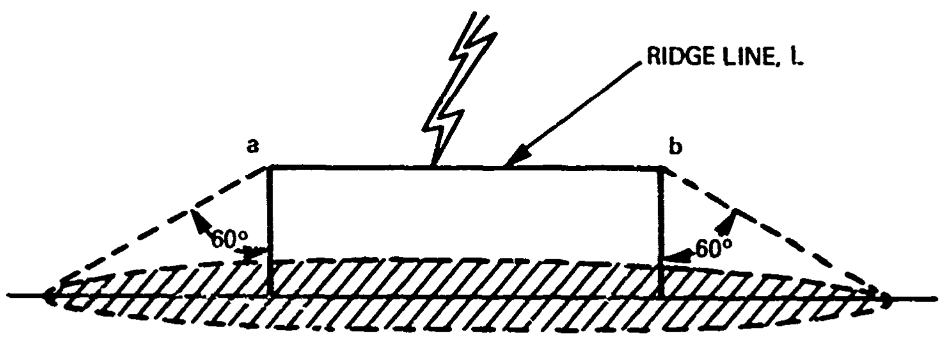
The lightning protection zone is the area under the apex of an imaginary 120 degree cone or such a cone normal to its axis, when either the apex, or the ridge line developed by the lateral motion thereof is considered a conductive discharge point. This point is accordingly directed at the lightning source and made suitably conductive to the cone base or ground. This is based on the assumption that the dielectric strength is high enough to withstand the voltage.

Close riveted skin construction that divides any lightning discharge path over a number of rivets is adequate to provide a lightning discharge current path.

Provisions for the protection of external sections must be proved adequate in laboratory tests. Details of the tests are given in MIL-B-5087B.



(A) LIGHTNING PROTECTIVE ZONE CREATED BY A SINGLE CONDUCTIVE POINT P, SUITABLY GROUNDED.

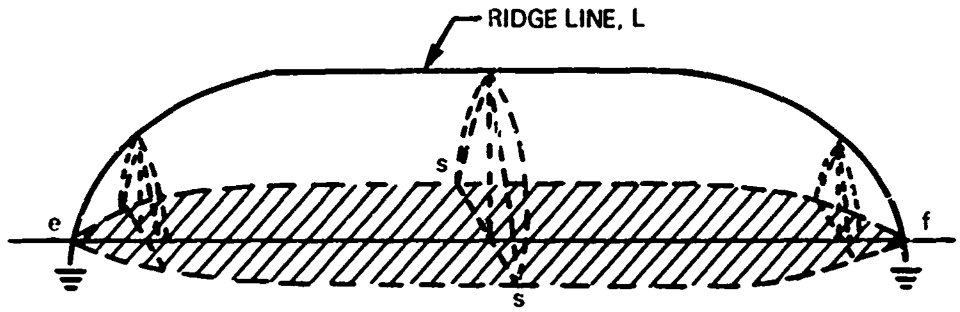


(B) PROTECTIVE ZONE CREATED BY A CONDUCTIVE RIDGE LINE, L, SUITABLY GROUNDED. (THIS ZONE MAY BE CONSIDERED AS DEVELOPED BY A SIMPLE MOTION OF TRANSLATION OF THE CONE IN FIGURE 11-8 (A) FROM POINT a, TO POINT b, ABOVE)

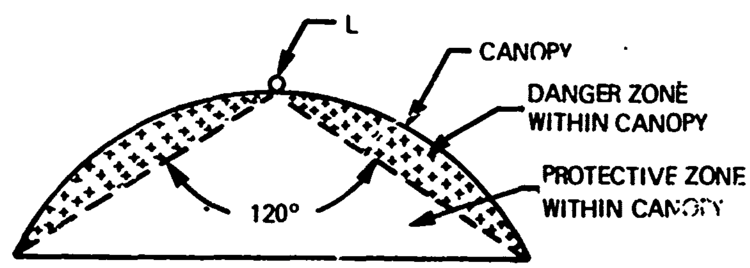
FIGURE 11-8 LIGHTNING PROTECTIVE ZONES

When bonds are sealed to protect against corrosion, tests must be performed to show that lightning discharge can be handled by the technique.

Protection of antenna housings adds the additional requirement that the antenna function must not be adversely affected. The surface-conductive path may be broken by gaps to avoid effects on the antenna pattern. These gaps should not exceed 1/16 of an inch.

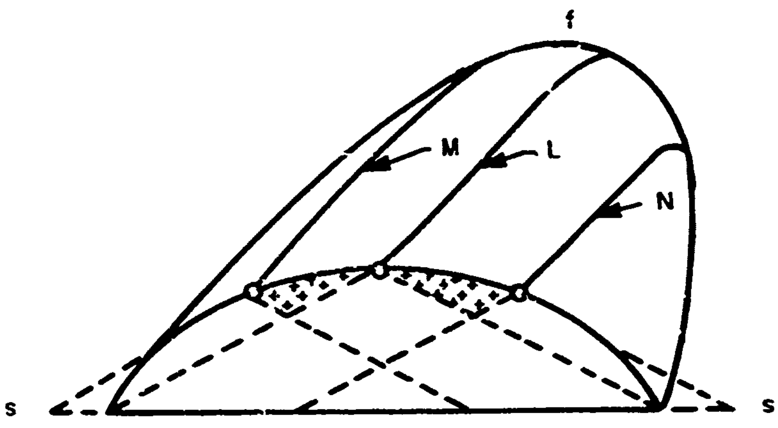


(C) PROTECTIVE ZONE CREATED BY A SINGLE GROUNDED CONDUCTOR, L, LAID CENTRALLY OVER RIDGE OF TYPICAL DIELECTRIC CANOPY OR BLISTER. (THIS ZONE MAY BE CONSIDERED AS DEVELOPED BY A COMBINED RADIAL AND TRANSLATORY MOTION OF THE APEX, FROM e TO f)



(D) SECTIONAL VIEW TAKEN THROUGH FIGURE 11-8 (C) AT s-s SHOWING INADEQUATE PROTECTIVE ZONE CREATED WITHIN CANOPY WITH BUT A SINGLE CONDUCTOR, L, INSTALLED AS SHOWN HERE AND IN FIGURE 11-8 (C).

FIGURE 11-8 LIGHTNING PROTECTIVE ZONES (CONTINUED)



(E) PERSPECTIVE OF SECTION s-f-s SHOWN IN FIGURES 11-8 (C) AND 11-8 (D). SHOWING HOW A COMPOUND PROTECTIVE ZONE MAY BE BUILT UP BY INSTALLATION OF ADDITIONAL GROUNDED CONDUCTORS, M AND N. WHICH PRODUCE OVERLAPPING PROTECTIVE ZONES.

FIGURE 11-8 LIGHTNING PROTECTIVE ZONES (CONCLUDED)

Class R bonding (RF potentials)

A low impedance path must be provided from the structure to the enclosure of all electrical and electronic equipment that produces electromagnetic energy. The direct current impedance of this path must not be larger than 25 milliohms.

All conducting material with any linear dimension greater than 12 inches or installed within one foot of unshielded transmitting antenna lead-in, must be bonded to the structure. A direct metal-to-metal bond is preferred. If jumpers must be used, keep them as short as possible. Aircraft skin must be designed so that a uniform low impedance is produced by the inherent RF bonding throughout construction. All structural elements of the aircraft must be RF bonded. Hatches, access doors, and inspection plates not near interference or wiring should be either permanently bonded or insulated from the aircraft skin, except for a protective static bond. Consideration must be given to insulation breakdown or intermittent contact due to operational vibration and wear.

Class S bonding (static charge)

Except antennas, all conducting items that have any linear dimension greater than 3 inches and that are external to the aircraft, carry fluids in motion,

or are otherwise subject to frictional charging, must have a mechanically secure connection to the vehicle structure. This connection must have a resistance of less than one ohm when dry.

Bonding connections must be installed so that vibration, expansion, contraction, or relative movement encountered in normal service use will not cause the resistance of the bond to vary during movement. Bonding connections should be located in a protected area whenever possible and in an area readily accessible for rapid inspection or replacement.

MIL-B-5087B lists the following requirements for bonding connections:

a. Parts shall be bonded directly to the basic structure rather than through other bonded parts.

b. Shielded wire grounds shall be carried through the pins of a connector or attached directly to the basic structure. Bonding through the connector shells is permitted, if the resistance through the shell is not greater than 2.5 milliohms.

c. Bonding jumpers shall be installed so that movable components are not impeded by the jumper in their operation.

d. Bonding connections shall not be compression-fastened through nonmetallic materials.

e. Bonds on plumbing lines shall not be dependent on mounting clamps due to differential thermal expansion. Clamp and jumper assemblies shall be used for bonding purposes.

f. All current returns and bonds for avoidance of explosion hazards shall be measured.

BONDING TECHNIQUES

There are two general kinds of bonds: permanent and semipermanent.

Permanent bonding joints can be made by:

a. Welding, including exothermic processes
b. Brazing
c. Sweating or swaging

One of the most effective techniques is exothermic welding. This method is simple to use, economical, and has a very wide application. It consists of clamping a preformed graphite mold around the items to be bonded and igniting a mixture of copper oxide and aluminum within the mold, assuming the two items to be joined are both copper. The thermal reaction heats the joint to 4200 degrees Fahrenheit. Test data has shown that the two items that were joined become a homogeneous unit and that there is no increase in resistance across the joint.

Thermal means of making a bond include welding, brazing, and soldering. These methods depend upon raising the temperature of the members to be bonded to cause surface plasticity. While this is occurring, an additional welding, brazing or soldering material is introduced that will easily adhere to the surfaces to be joined. The aim of this technique is to form a joint that is completely homogeneous with the parts to be joined.

These thermal methods, however, vary widely as to the temperatures involved. They range from soldering temperatures of 300 to 400 degrees Fahrenheit, to welding temperatures of 3000 to 4000 degrees Fahrenheit. Because of these wide thermal differences and the resulting changes that occur in the materials to be joined, the materials will require different degrees of surface preparation. Assume that there are two pieces of copper bar 1/4 inch by 1 inch to be bonded. If they were mechanically bolted together and solder was then applied, the temperature of the joint would hardly go above 400 degrees Fahrenheit. This is only enough heat to drive off water vapor or moisture that may be adhering to the surface, but would certainly not drive away any surface impurities of the copper bar.

If the two parts were to be brazed, they would be subjected to heats of around 2000 degrees Fahrenheit, which is high enough to boil off a great number of the surface impurities and would even be effective against most of the oxides and sulfide. If the same two bars were to be joined together by welding, for example, using the exothermic process, the joint would be subjected to approximately 4000 degrees Fahrenheit. At such a temperature, all the impurities, including the oxides and sulfides, boil to the surface and are deposited as slag, which has practically no ability to adhere to the welded joint and is readily removed. The only risk of impurties being entrapped depends on the quality of the exothermic welding materials, and since high quality products are readily available, this need not be of any concern.

Semipermanent joints that must be occasionally disconnected for maintenance can be made by:

a. Lock threaded devices
b. Rivets
c. Clamped fittings

Tooth-type lock washers are used with lock threaded devices to increase the area of contact between the two surfaces.

Ordinary conduit clamps cannot be used to join flexible conduit since they cover a relatively small surface area and the pressure required to make a good bond would be great enough to collapse the conduit wall. For this use, a method that will spread this force over a large area and also provide a larger area of contact is desirable. A good design solution is a flared split sleeve that is fitted around the conduit. An even better bond will result if this sleeve is soldered to the conduit through perforations in the sleeve.

In bonds made by strictly mechanical means, the emphasis is on creating intimate physical contact between the two surfaces by bringing them as close together as practical. This depends upon perfect smoothness of the mating surfaces and pressure brought on the members in joining them. With such a bond, all the pressure that can be applied within the physical constraints of the system can never overcome the difficulties of poor surface preparation. Great mechanical force can have very little effect when the two conductors are separated by an insulating layer of oxidation, a sulfide film, or any other nonconducting substance. If the surface should have sulfide compounds on it, the situation would be made worse by joining the two surfaces under pressure. It

is for this reason that great care must be taken in preparing the bonding surfaces when mechanical means are used to bond them together. The best bonds are made when the surfaces are made scrupulously clean immediately before any attempt to bond them.

Contaminants that affect the surfaces of metals are of two categories: those foreign to the material and those that result from a chemical reaction between the conductor and its environment. The first category includes those substances which make the conductor merely "dirty." The material must be physically clean: dust, dirt, foreign substances, lint, sawdust, and packing material must be removed by wiping, dusting, or brushing. Then foreign material such as oils and greases must be removed by using solvents for the specific materials involved.

There are many solvents that dissolve greases and other hydrocarbons. Vapor degreasing is a good method to use. Surfaces to be cleaned should be exposed to vapor degreasing until the surface has reached the temperature of the vapor. Then solvents such as trichloroethylene or perchloroethylene should be used. In extreme cases, the surfaces can be further cleaned using an acid bath of chromic and sulfuric acid. This is a very strong degreasing procedure and the material should be dipped into the bath for only a few seconds so it will not be attacked by the acid When the material is removed from the bath, take great care to assure that all the acid liquid is washed away by flushing with running cold water, followed by a hot water rinse for rapid air drying.

The next cleaning consideration is the removal of surface substances caused by the action of a substance in the environment on the material. The principal offender is oxidation of the material.

Practically all materials in every kind of environment have this problem to some degree. A moist environment will make oxidation more rapid which will make more careful cleaning necessary. For some materials such as copper and aluminum, the oxides protect the surface from further oxidation so that once the initial oxide coating is removed, the surface is ready to be bonded. This oxide can be removed by wire brush, steel wool, and other abrasives. It is important that the surface be cleaned of the byproducts of this oxide removal before the bond is made. In the case of steel, however, unless it is stainless steel which does not readily oxidize, the problem is more severe because the oxide coating continues to build up and sometimes it may be thick enough to damage the place to be bonded. It too can be removed by wire brush and steel wool, but the depth of the oxide penetration is important.

In certain environments, the sulphur compounds have an important concentration. This tends to form coatings of sulfides on the material surfaces that are quite difficult to remove. Strong acid baths are necessary, but these may have a deleterious effect on the material. In general, materials that have sulfide coatings should not be used. In the case of indirect bonding where a jumper is used, screws or washers that have been anodized, or materials with anodic finishes should not be used because of the great difficulty in removing such substances.

Some bonding designs that are commonly used are shown in the following

figures. Figure 11-9 shows the bonding arrangement for a vibration isolator. The bonding of a connector is shown in Figure 11-10. Instructions are given for the area of mating surface to be cleaned. Figures 11-11 and 11-12 show typical bolted members and bracket installation. It is important to include instructions for surface preparation on shop drawings. Two types of bonding are shown in Figure 11-13. The hard bond is preferred over the jumper type bond in all cases.

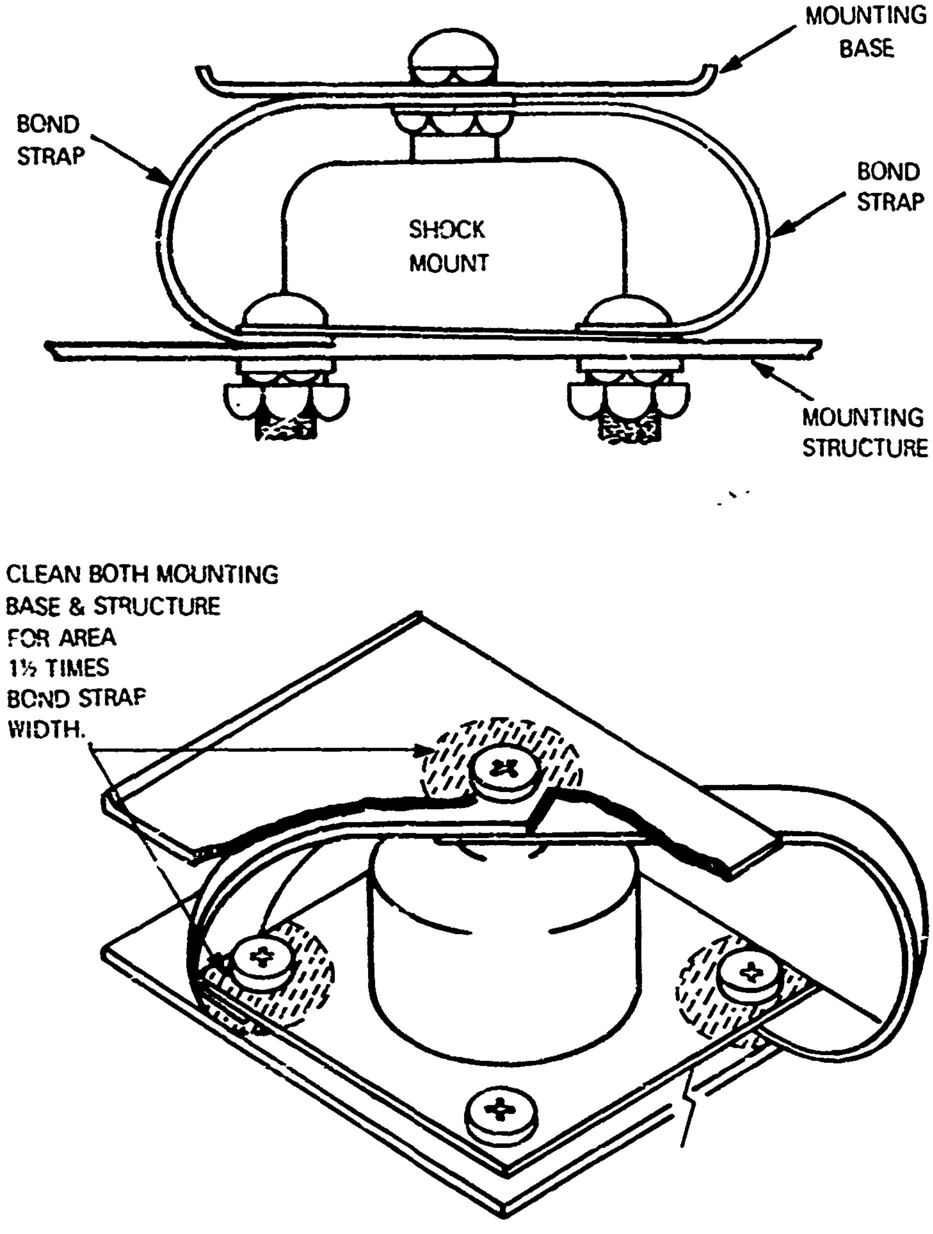


FIGURE 11-9 BONDING OF VIBRATION ISOLATOR

Many materials that are used in bonding have been plated or covered with conductive finishes. In both cases, the surface must be brought to the original condition before bonding. Paint, lacquer, plating, and finishes can usually be removed by wire brush or steel wool, but it is also important to remove the debris of the cleaning process. After the finishes have been removed, the problem remains to see that the metal surfaces are clean. The same procedures previously described should be used. Whenever protective coating is removed in preparation for bonding two surfaces together, MIL-B-5087B requires that the surface of the completed bond be refinished with the original finish or another suitable one within 24 hours after inspection of the bond.

Cleaning agents to clean surfaces include acids to remove serious hydrocarbon coatings, solvents that will remove ordinary hydrocarbon films, and hot and cold water rinses. Special applications will require special cleaning agents. Cleaning agents remove unwanted substances but they themselves can have a very detrimental effect on the surfaces to be cleaned. It is important to use them only long enough to break down the surface adherence of the foreign substance. The material surface must be made perfectly clean of the cleaning agent before the bond is made. If this is not done, the material itself will deteriorate and the best bond is of no use. Abrasives such as emery cloth and sandpaper are corrosive because their particles embed themselves in the metal. Therefore they should not be used. Large quantities of cold water used after a

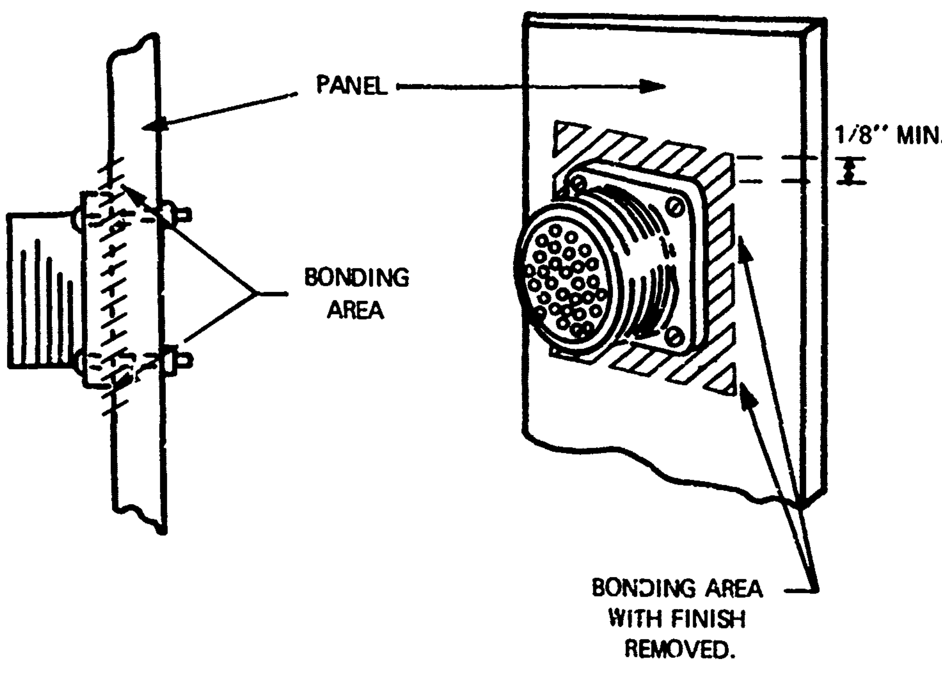


FIGURE 11-10 BONDING OF A CONNECTOR

strong cleaning agent such as acid will dissolve any of the agent remaining on the surface. The use of hot water as the final cleaning agent is recommended because, in addition to being a good solvent, it has the added property of encouraging rapid drying of the surface.

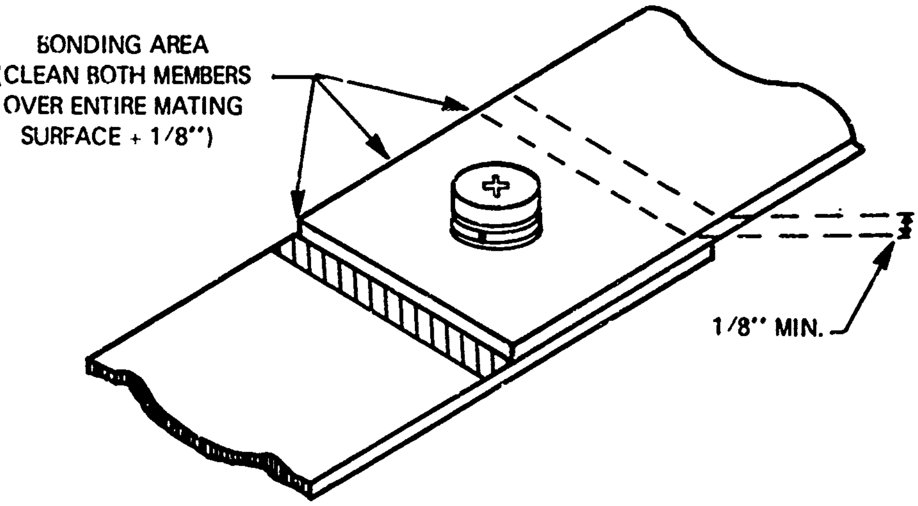


FIGURE 11-11 BOLTED MEMBERS

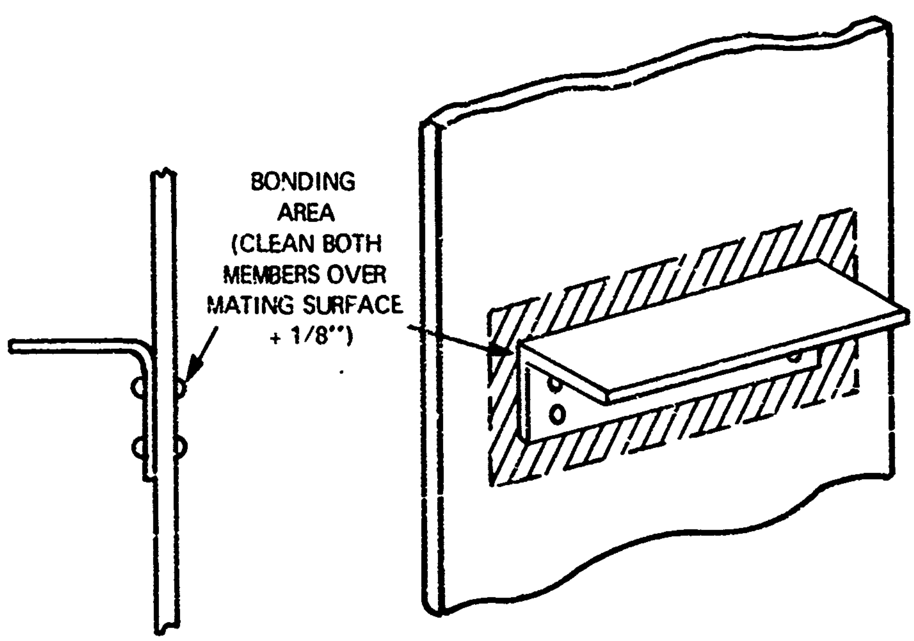
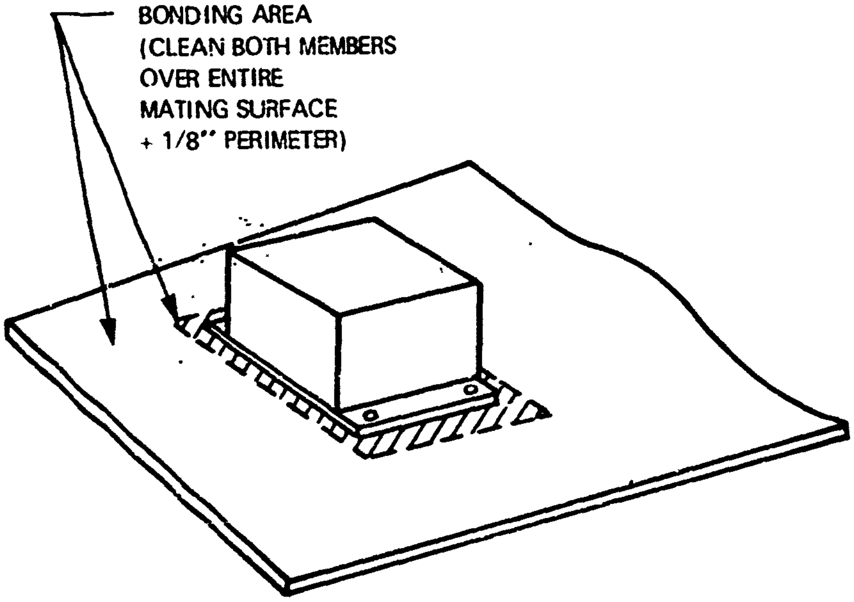
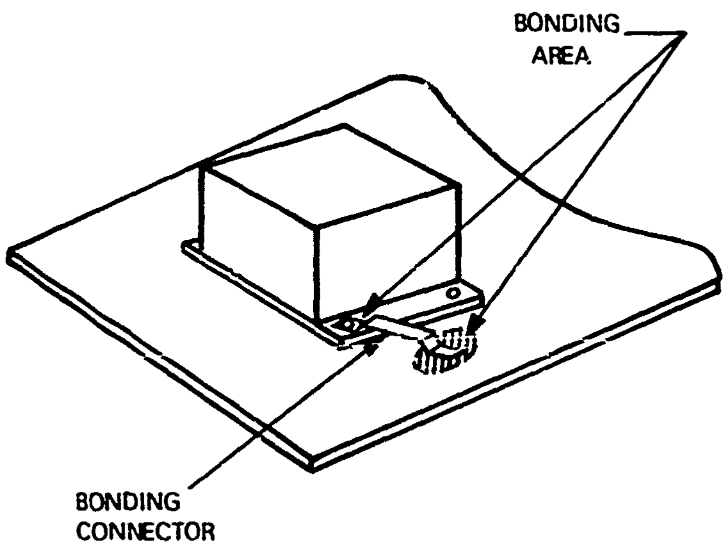


FIGURE 11-12 BRACKET INSTALLATION (RIVET OR WELD)



HARD BONDED

(A)



JUMPER BONDED

(B)

FIGURE 11-13 BASE MOUNTED COMPONENTS

From the foregoing discussion, it can be seen that once the method of making the bond has been established, the degree of surface preparation can also be specified. No particular care has to be exercised in welded bonds as opposed to the extreme care required in mechanical bonds. This is a very important cost factor and should be considered in specifying bonding techniques. A method that requires less surface preparation will certainly be less costly. This, together with the other obvious features of welding and brazing that have been described, makes these the optimum methods on most installations.

Several methods can be used for minimizing corrosion and its adverse effect on bonding. One is the use of metals low on the activity table. Another is minimizing the amount of moisture that can get into the joint. Joints should be assembled dry and held together at high pressure to minimize the possibility of moisture getting into the joint. The joint can be covered with a protective coating that will further reduce the intrusion of moisture. Additional finishes such as paint and plating should be specified with caution. Finishing of the anode material alone may produce severe corrosion at any finish imperfection. When dissimilar metals are in contact, avoid covering the surface of the anodic material only; either cover the surface of both metals or only the cathode. This is due to the unfavorable anode-to-cathode ratio previously explained.

When the bond is easily accessible for inspection and maintenance, a replaceable washer made of the more active of the two metals may be inserted between the parts to be bonded. This washer will receive the brunt of the corrosion and can easily be replaced.

In discussing the various bonding techniques, the question of the effectiveness of the bonding must be considered. It was shown in Equation 11-8 that the value of L of a straight bonding strap can be obtained empirically. Practical experience based on many bonding installations has shown that as the value of L goes above 0.025 microhenry, the bonding effectiveness goes down. The length-to-cross-section ratio determines this value of L, consequently the 3-to-1 ratio mentioned previously is important. If values of L stay below 0.025 microhenry, an effective bond can be achieved by a single strap or several straps in parallel and suitably spaced. If a single strap is used, however, its physical relationship to the bonded member is important because the capacitance factor will then be affected. Saturation bonding, which is the trade-off between the use of one or of more than one bonding straps (where bonding effectiveness is improved by less than 10 percent), is achieved with the addition of another bonding strap and occurs at about 0.018 microhenry.

The effectiveness of the bond then depends on its application, frequency range, magnitude of current, and environmental conditions such as vibration, temperature, humidity, fungus, and salt spray. To accommodate these various considerations, criteria to provide good bonds are summarized as follows:

a. Bonding must never damage the two surfaces that are to be joined.

b. Bonds are best made by joining similar metals unless the material has a high natural contact resistance. In that case, a transfer material will yield a better bond. If this is not possible, then the more detailed rules previously given are to be followed.

c. Bonds should make good metal-to-metal contact over as much of the mating surface as possible. The mating surfaces should be free from all nonconducting finishes. Bare metal-to-metal contact alone will not ensure a low impedance connection between mating surfaces because, in theory, mating between two surfaces is only assured at three points.

d. Bonding jumpers are only substitutes for direct bonds. If the jumpers are kept short, and are higher in the electrochemical series than the bonded members, they can be considered reasonable substitutes.

e. Bonds are subject to corrosion and are susceptible to problems caused by mechanical shock and vibration. Their accessibility for preventive and unscheduled maintenance is a key design consideration.

f. The bonding jumper or direct bond must be able to carry the currents that will flow through it. This is particularly true in bonding to the ground system where appreciable currents may flow and also in bonding for protection of equipment against lightning.

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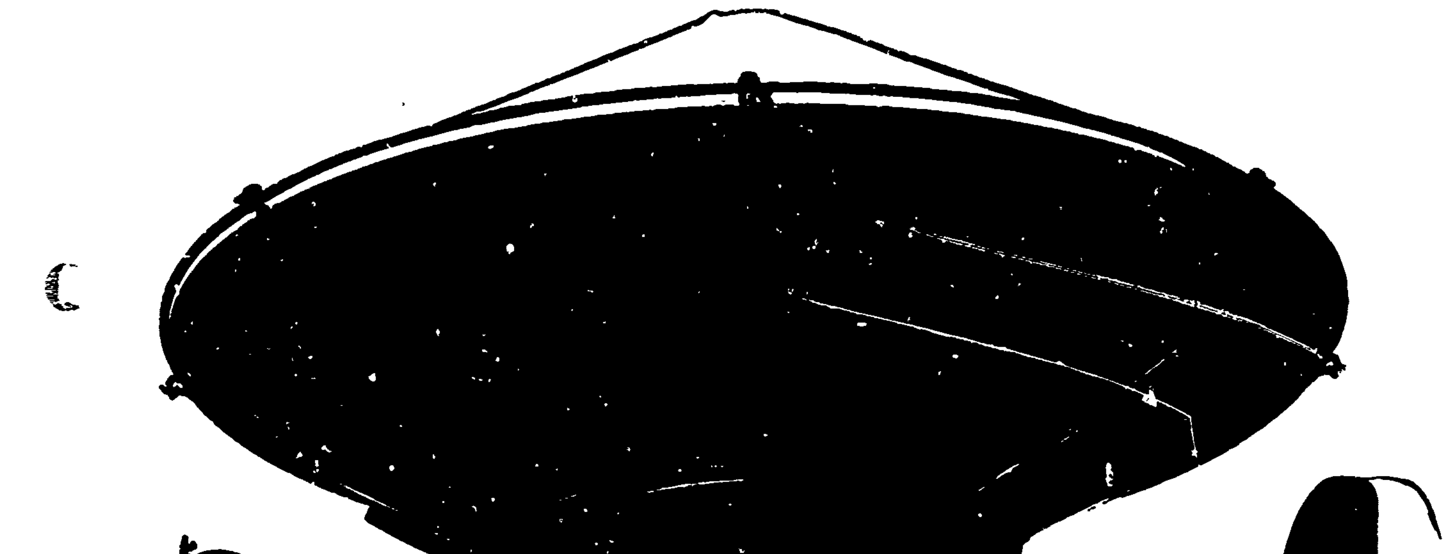
NAVAL AIR SYSTEMS COMMAND

ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 12



PUBLISHED BY DIRECTION OF COMMANDER, NAVAL AIR SYSTEMS COMMAND

CHAPTER 12
SHIELDING DESIGN

CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

In using electronic instrumentation, communications, navigation, and control systems, there are many ways to prevent radiation or to protect sensitive receptors. Electromagnetically shielded enclosures range in size from small component cases to large shielded buildings such as the shielded hangars in which complete aircraft can be tested. The discussion in this chapter is limited to basic shielding fundamentals and their application to equipment cabinets and shielded rooms.

The application and use of shielded enclosures is relatively simple. They are used to control the RF ambient of a given region. Thus these shielded enclosures are used to exclude RF energy, to contain it, and in many cases, both. The shielded enclosure can be thought of as a way to separate parts of a system or systems. Systems can be isolated by increasing the spacing between them, but where space is limited, as in an aircraft, shielding is a more convenient and practical method.

A typical use for a shielded room is to provide an RF-free area in which to make measurements required by the various military EMC specifications and standards, such as MIL-I-6051D, MIL-STD-461A, and MIL-STD-462. These specifications and standards require an RF ambient level lower than the test limits of the specification or standard. In most readily accessible areas, the RF ambient level is greater than this. Thus the need for a shielded room is established and the shielding requirements are determined.

THEORY OF ELECTROMAGNETIC SHIELDING

BASIC PRINCIPLES AND PRACTICES

Almost all electrical and electronic equipments can emit or respond to extraneous electrical or magnetic energy. An ideal transmitter would transmit only functional energy, and an ideal receiver would respond only to that energy. The basic problem in achieving electromagnetic compatibility is to design a system that allows each equipment to operate in conjunction with other equipments without causing or suffering degradation of operation.

This problem could be overcome by installing the equipment in an enclosure that would completely prevent unwanted energy from leaving or entering equipment. Such an enclosure would be ideal and although such a shield cannot exist, practical shields can be built that effectively suppress unwanted electrical and magnetic energy.

Airborne equipments pose special shielding problems because the equipments must be mounted close together and there are often high energy fields near susceptible devices.

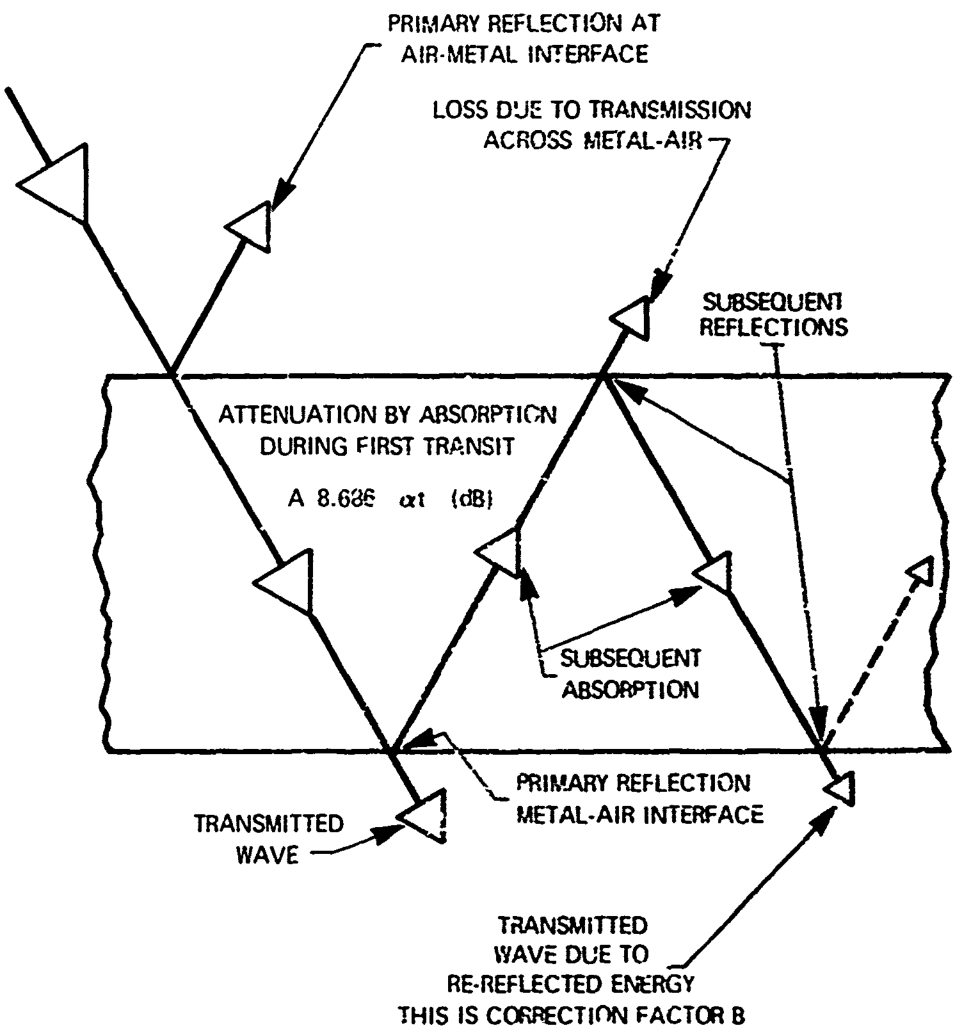


FIGURE 12-1 ATTENUATION OF AN ELECTROMAGNETIC WAVE BY A METALLIC BARRIER

The use of a single electromagnetic shield reduces the propagation of undesired energy in two ways:

1. The energy entering the shield is attenuated as it travels through the shield. For discussion, this parameter will be designated as absorption loss, A.

2. A certain percentage of the energy reaching the shield is reflected. This phenomenon will be designated reflection parameter, R.

When evaluated in terms of decibels, the shielding effectiveness is the sum of these two factors:

$$S = R + A \qquad (12\text{-}1)$$

Figure 12-1 shows how electromagnetic energy is reduced by a shield. When a shield has an absorption loss A of less than 10 dB, a positive or negative correction value must be added to the shielding effectiveness making the equation:

$$S = A + R + B \qquad (12\text{-}2)$$

where B is the correction term for re-flection. In most cases B can be ignored, but it must be considered at frequencies for which shielding is required against magnetic fields. B correction factors for a solid metal sheet are given in Table 12-1.

Consider the shielding enclosure to be a metal envelope enclosing an electric circuit. To facilitate the development of this shielding theory, the envelope is assumed to be either a cylinder or a sphere even though enclosures may be of other shapes. The equations developed apply only to these idealized shapes, but are helpful in understanding the factors involved in other shapes. The first consideration will be at high frequencies where waves are greatly attenuated in passing through the shield: then low frequency will be discussed where impedance mismatch at the shield-air interface results in substantial loss through reflection.

Consider two parallel conductors carrying current in opposite directions and contained in a cylindrical shield. This is represented in Figure 12-2, where the thickness of the shield, t, is given by: $(d_1 - d_2)/2 = t$: If the thickness of the shield is small with respect to the radius, the propagation may be considered as plane-wave propagation. From electromagnetic wave theory, the propagation constant, $\underline{\sigma}$ for a uniform plane wave is described by:

$$\underline{\sigma} = \alpha + j\beta = j\omega - \mu_m \epsilon_m \left(1 + \frac{g_m}{j\omega\epsilon_m}\right) \qquad (12\text{-}3)$$

where:

α = attenuation constant, nepers per meter

β = phase constant, radians per meter

μ_m = permeability of the material

TABLE 12-1 B CORRECTION FACTOR FOR A SOLID METAL SHIELD

	Shield Thickness (mils)	60 Hz	100 Hz	1 kHz	10 kHz	100 kHz	1 MHz
Magnetic Fields Copper ($\mu = 1, G = 1$)	1	-22.22	-24.31	-28.23	-19.61	-10.34	-2.61
	5	-21.30	-22.07	-15.83	- 6.98	- 0.55	+0.14
	10	-19.23	-18.59	-10.37	- 2.62	+ 0.57	–
	20	-15.35	-13.77	- 5.41	+ 0.13	- 0.10	–
	30	-12.55	-10.76	- 2.94	+ 0.58	–	–
	50	- 8.88	- 7.07	- 0.58	–	–	–
	100	- 4.24	- 2.74	+ 0.50	–	–	–
	200	- 0.76	+ 0.05	–	–	–	–
	300	+ 0.32	+ 0.53	–	–	–	–
Electric Fields and Plane Waves Copper ($\mu = 1, G = 1$)	1	-41.52	-39.31	-29.38	-19.61	-10.33	-2.61
	5	-27.64	-26.46	-15.82	- 6.96	- 0.55	+0.14
	10	-21.75	-19.61	-10.33	- 2.61	+ 0.57	–
	20	-15.99	-13.92	- 5.37	+ 0.14	- 0.10	–
	30	-12.73	-10.73	- 2.90	+ 0.58	–	–
	50	- 8.81	- 6.96	- 0.55	+ 0.14	–	–
	100	- 4.08	- 2.61	+ 0.51	–	–	–
	200	- 0.62	+ 0.14	–	–	–	–
	300	+ 0.41	+ 0.58	–	–	–	–
Magnetic Fields Iron ($\mu = 1000, G = 0.17$)	1	+ 0.95	+ 1.23	- 1.60	- 1.83	–	–
	5	+ 0.93	+ 0.89	- 0.59	–	–	–
	10	+ 0.78	+ 0.48	+ 0.06	–	–	–
	20	+ 0.35	+ 0.08	–	–	–	–
	30	+ 0.06	- 0.06	–	–	–	–
	50	–	–	–	–	–	–

TABLE 12-1 (CONTINUATION)

	Shield Thickness (mils)	60 Hz	100 Hz	1 kHz	10 kHz	100 kHz	1 MHz
Electric Fields and Plane Waves Iron (μ = 1000, G = 0.17)	1	-19.53	-17.41	- 8.35	- 1.31	–	–
	5	- 6.90	- 5.17	+ 0.20	–	–	–
	10	- 2.56	- 1.31	+ 0.36	–	–	–
	20	+ 0.16	+ 0.54	–	–	–	–
	30	+ 0.58	+ 0.42	–	–	–	–
	50	+ 0.13	–	–	–	–	–

ϵ_m = dielectric constant of the material

g_m = conductivity of the material

ω = $2\pi f$

j = $\sqrt{-1}$

Even for imperfect conductors, the displacement currents may be regarded as being much smaller than the conduction currents. That is:

$$\frac{g_m}{\omega \epsilon_m} >> 1 \qquad (12\text{-}4)$$

Modifying Equation 12-3, the propagation constant for an imperfect conductor becomes:

$$\sigma = (1 + j) \sqrt{\pi f \mu_m g_m} \qquad (12\text{-}5)$$

or equivalently:

$$\sigma = (1 + j)\alpha \qquad (12\text{-}6)$$

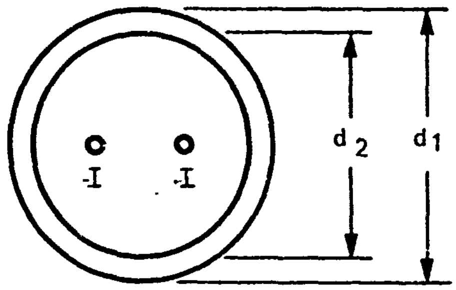


FIGURE 12-2 ELECTROMAGNETIC SHIELDING THEORY

Where tne attenuation and phase constants each equal

$$\sqrt{\pi f \mu_{m} g_m}$$

Thus, every time the wave passes through the shield, its power loss or attenuation, A, will be:

$$A = \alpha t \text{ nepers} = 8.686\, \alpha t \text{ (dB)} \tag{12-7}$$

where 1 neper ≈ 8.686 dB.

Reflection of energy at the boundary of two different media is due to the change in impedance which affects the incident wave. As in transmission line theory, a change of impedance introduces a mismatch causing a percentage of the incident energy to be reflected. In the cylindrical shield problem being considered, energy is passing through space, which has an intrinsic impedance of η_s, and striking upon a medium of intrinsic impedance, η_m. The intrinsic impedance of any medium is defined as:

$$\eta = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{j\omega\mu_m}{g_m + j\omega\epsilon_m}} \tag{12-8}$$

For the imperfect conducting medium where $g_m >> \omega\epsilon$, and assuming $t << d_2$:

$$\eta_m = \sqrt{j\frac{2\pi f \mu_m}{g_m}} \tag{12-9}$$

$$\eta_m = (1 + j)\sqrt{\frac{\pi f \mu_m}{g_m}}$$

If the shield is relatively close to the source, the impedance in the radial direction due to two closely spaced wires has been shown to be:

$$Z_\rho = j\omega\mu_o\rho \tag{12-10}$$

where:

μ_o = permeability of free space, Henries/meter

ρ = radial distance, meters

If K is defined as the ratio of the two impedances:

$$K = \frac{Z_m}{Z_\rho}, \tag{12-11}$$

then for waves normally incident upon the shield:

$$K = \frac{\eta_m}{Z_\rho} = \frac{(1 + j)\sqrt{\frac{\pi f \mu_m}{g_m}}}{j\omega\mu_o\left(\frac{d_2}{2}\right)} \tag{12-12}$$

From electromagnetic wave theory, the loss, R, due to reflections at both sides of the shield is:

$$R = 20 \log_{10} \frac{|K + 1|^2}{4|K|} \tag{12-13}$$

For sharp discontinuities in impedance levels, Equation 12-13 may be simplified:

$$\text{For } Z_\rho >> \eta_m\text{:} \quad R = 20 \log_{10} \frac{1}{4|K|} \tag{12-14}$$

$$\text{For } \eta_m >> Z_\rho\text{:} \quad R = 20 \log_{10} \frac{|K|}{4}$$

The reflection loss may be small or large. For magnetic shields, the reflection loss is usually small or negative at low frequencies. An iron shield with a relative initial μ of 100 and a conductivity 1/5 that of copper, has a radial impedance Z_ρ

that is increased by a factor of $\sqrt{500}$ when compared to copper. This brings the value of Z_ρ to $0.008\sqrt{j}$. The impedance ratio becomes nearly 0.1, and this makes the reflection loss comparatively small.

The radial impedance in metals is proportional to $\sqrt{f}$. Therefore, this impedance ratio is about 1 at 10 kHz and the reflection loss is negligible. But in magnetic shields, the attenuation constant is larger than in nonmagnetic shields. For the iron shields just mentioned, the attenuation constant is increased by a factor of $\sqrt{20}$, or approximately 4.5. A thick shield will, therefore, compensate for lack of reflection loss. For a thin shield, R will become more important than A, and for this reason (where B is negligible) a nonmagnetic shield may be more effective at intermediate frequencies than a magnetic shield. At an interface between two different metals, the impedance mismatch is independent of frequency. Advantage can be taken of this fact by using a shield made of two metals, copper and iron for example, with the copper on the outside to take advantage of the large reflection losses at the boundary between copper and air.

There are many new ideas used in the latest designs for shielded enclosures. All of these ideas are directed toward overcoming some major problems in existing enclosures and increasing the effectiveness of the shields in a more intense and more complex electromagentic environment. Of major concern is the extension of the upper and lower frequency limits of shielded enclosures. Lower frequency limits are being overcome by use of high-permeability materials, such as mu-metal, in greater thicknesses but at higher cost and with greater susceptibility to magnetic saturation and strain. Higher frequency limits are being overcome by the use of improved seams to reduce RF leakage. For large enclosures, heavy-gauge low carbon steel offers an economical and satisfactory solution to both problems.

Preformed corners are used to eliminate trihedral and dihedral joints. Another serious problem that is being overcome by shielded enclosure designs is that of internal standing waves. Standing waves are being reduced by the use of electromagnetically lossy material on the inside of the enclosure. This material is electrically analogous to the material used in construction of acoustic anechoic chambers and is an effective solution to this problem.

SHIELDING EFFECTIVENESS

MEDIUM OF PROPAGATION AND TYPES OF SHIELDS

When shielding is used to reduce the undesired intrusion or escape of energy, the properties of the electromagnetic field determine the degree of impedance mismatch as the field encounters a given shield. Thus it is desirable to examine the characteristics of electromagnetic fields in general before proceeding further.

Near a radiator, antenna, or other energy source, the characteristic impedance of the field is related to the source impedance. If the source is a high

impedance, as associated with a rod antenna or a circuit element with a high voltage-to-current ratio, the resultant field is predominantly electric and has an impedance greater than 377 ohms. A low impedance source, such as a loop antenna or a circuit element with a high current-to-voltage ratio, creates a predominantly magnetic field with an impedance of less than 377 ohms.

As the wave propagates away from the source, energy distribution is equalized between the electric and magnetic components of the field. At a distance of $\lambda/2\pi$ (approximately 1/6 of a wavelength) from a point source, the magnitude of the impedance rapidly approaches 377 ohms.

Analysis of field impedance is based on a typical antenna, such as the rod or loop. In practice, these antennas are represented by circuit elements and their connecting wires or leads. The field generated around a high-voltage rectifier will be predominantly an electric or high-impedance field, while the field around a relay coil will be predominantly magnetic or low impedance.

The impedance of any field is given by:

$$Z_w = \frac{E}{H} \tag{12-15}$$

where:

Z_w = the wave impedance

E = the electric field

H = the magnetic field

For a high impedance source this is given by:

$$Z_w = \frac{1}{c\epsilon_o} = 377\Omega \qquad \text{if } r >> \lambda \tag{12-16}$$

or, for a short electrical (rod) antenna

$$Z_w = \frac{j}{\omega\epsilon_o r} \qquad \text{if } r << \lambda$$

wherein:

r = the distance from the source to the shield in meters

λ = the wavelength in meters

ϵ_o = the dielectric constant of free space (8.85×10^{-12} farad/meter)

c = the velocity of light in free space (3×10^8 meter/sec)

$\omega = 2\pi f$

For a low impedance source, this is given by:

$$Z_w = c\mu_o = 377\Omega \qquad \text{if } r >> \lambda$$

and, for a short magnetic (loop) antenna, (12-17)

$$Z_w = j\omega\mu_o r \qquad \text{if } r << \lambda$$

where μ_o = the permeability of free space (1.26×10^{-6} Henry/meter). In reality, these reactive impedances cannot result in the real power loss indicated in Equation 12-7. However, the mathematical procedure yields correct results.

A second important factor in determining the nature of the field impedances is the distance from the source. Close to the source, most of the energy will be contained in the induction field. This region is known as the "near field region" or "Fresnel region." If the parameter of r_n is defined as the distance from the source at which 99 percent of the total energy is contained in the induction field, this field may be said to predominate over the range where:

$$r \leqslant r_n = \frac{0.01c}{\omega} \text{ meters} \tag{12-18}$$

where c = velocity of propagation (meters/sec.)

At distances far from the source, most of the energy will be contained in the radiation field. This region is known as the "far field region" or "Fraunhofer region." The energy in this field is equally divided between the electric and magnetic components. If the parameter r_f is defined as the distance from the source where 99 percent of the total energy is contained in the radiation field, this field may be said to predominate over the range where:

$$r \geqslant r_f = \frac{100c}{\omega} \text{ meters} \tag{12-19}$$

If energy of different frequencies is present, the magnitudes that must be kept out can be identified. At a low frequency, the large amount of energy in the induction field is quite close to the source, but the radiation field is too far away to be of any consequence. At high frequencies such as 1 GHz, the radiation and induction fields have large amounts of energy close to their sources. Table 12-2 shows a summary of these facts at different frequencies. Table 12-2 shows that, for most EMI sources below 1 MHz in close proximity, induction field shielding is required. The frequencies above 1 GHz require shielding that is effective against both radiation and induction fields. This is why in the consideration of shielding, the induction field is so important; from the lowest frequencies to the highest, its energy is concentrated close to the source.

Based on these relationships and those previously discussed, the reflection and absorption losses in fields of various types may be readily calculated.

Frequency (f)	Distance from Source (meters)	
	Radiation Field	Induction Field
1 kHz	4,780,000	478
1 MHz	4,780	0.478
1 GHz	4.78	0.000478
1000 GHz	0.00478	0.000000478

TABLE 12-2 DISTANCE OF RADIATION AND INDUCTION FIELDS FROM SOURCE AT DIFFERENT FREQUENCIES

Shielding in the near region is relatively simple when high impedance (or electric) fields are concerned. The reflection loss, R, for such a high impedance field is found as follows:

$$K = \frac{Z_m}{Z_w} = (j - 1)\,(\omega\epsilon_o r)\sqrt{\frac{\pi f \mu_m}{g_m}} \qquad (12\text{-}20)$$

where:

K = ratio of impedances

Z_m = impedance of material

Z_w = wave impedance

j = $\sqrt{-1}$

w = $2\pi f$ where f is the frequency

ϵ_o = dielectric constant of free space

r = distance from source to shield

μ_m = permeability of material

g_m = conductivity of material

Substituting the relative value of conductivity referred to copper, where:

$$g_m = Gg_c$$

$$= (0.582 \times 10^8)G \text{ mhos/meter} \tag{12-21}$$

and the relative permeability referred to free space, where:

$$\mu_m = \mu_o \mu$$

$$= (4\pi \times 10^{-7})\mu \tag{12-22}$$

and using distance r, in terms of inches, K becomes:

$$K = (j - 1)(3.68 \times 10^{-19}) \sqrt{\frac{f^3 r^2 \mu}{G}} \tag{12-23}$$

$$|K| = (5.2 \times 10^{-19}) \sqrt{\frac{f^3 r^2 \mu}{G}}$$

The reflection loss, R, follows from Equation (12-23):

$$R = 353.6 + 10 \log_{10} \frac{G}{f^3 \mu r^2} \tag{12-24}$$

wherein:

R = reflection loss in dB

r = distance from the shield to the source in inches

μ = relative permeability of the shield

G = conductivity referred to copper

f = frequency in Hertz

Since R is inversely related to the cube of the frequency, R will increase to its highest value as f decreases to its lowest value. At 60 Hertz, a portion of the energy is reflected. Since the energy is reflected, even screens or sheets of shielding material with holes are effective shields at low frequencies. At higher

frequencies, the penetration loss, A, becomes large and provides most of the attenuation. Penetration loss is given by:

$$A = 3.338 \times 10^{-3} \times t \sqrt{fG\mu}\ (\mathrm{dB}) \tag{12-25}$$

where t is the shield thickness in mils.

Since A is directly related to conductivity, G, and permeability μ, materials with high conductivity and permeability such as copper or steel are excellent shields for high impedance fields over the entire spectrum because as the frequency increases, so does the attenuation.

Low impedance or magnetic fields are not easily shielded at low frequencies. Shield materials for high impedance fields may be made to attenuate magnetic fields if the shield is designed with the proper physical configuration and oriented with respect to the field so as to present a shorted turn. Another way to deal with shielding of low impedance fields is to divert the field by using a path made of material of high permeability.

Shielding in the far zone, radiation field, is similar to shielding in the near zone except for the way in which reflection losses are calculated. The reflection loss for plane waves is given by:

$$R = 108.2 + 10 \log_{10} \frac{G \times 10^6}{\mu f}\ (\mathrm{dB}) \tag{12-26}$$

Since R is directly related to the quantity $G \times 10^6/\mu f$, it can be seen that materials with a high conductivity G, and low permeability μ, will yield a high reflection factor.

Absorption loss, A, is given by:

$$A = 3.338 \times 10^{-3} \times t \sqrt{fG\mu}\ (\mathrm{dB}) \tag{12-27}$$

The above equation shows that the absorption capability of a particular shield is dependent on a high value of the product of permeability and conductivity.

The techniques for determining shielding effectiveness may be extended similarily to account for various types of sources. The following paragraphs summarize the losses due to typical sources. The relationships have been derived for shielding materials but not for complete enclosures

For a low impedance source (loop at distance $<< \lambda/2\pi$):

$$R = 20 \log_{10} \left[\frac{0.462}{\left(\sqrt{\frac{fG}{\mu}}\right)r} + 0.136r \left(\sqrt{\frac{fG}{\mu}}\right) + 0.354 \right] \tag{12-28}$$

For a high impedance source (rod at distance $<<\lambda/2\pi$):

$$R = 354 - 10 \log_{10} \left(\frac{\mu f^3}{G} r^2\right) \tag{12-29}$$

For plane waves (loop or rod at distance $>>\lambda/2\pi$):

$$R = 168 - 10 \log_{10} \left(\frac{\mu f}{G}\right) \tag{12-30}$$

When the usefulness of the shielding is due to reflection loss, two or more layers of dissimilar shielding material, separated by a dielectric and yielding multiple reflection, will give a greater shielding effectiveness than the same amount of metal in a single sheet. A composite electric and magnetic shield of usable physical proportions can be made by using metals with good magnetic field absorption loss properties.

SHIELDING MATERIAL

The material used for a particular shield is determined by the attenuation desired, frequency range for which the attenuation is desired, and the acceptable limits of the thickness of the shielded enclosure. Ferrous metals, particularly of high permeability, are more effective shields at power line frequencies of 60 Hertz than are nonferrous materials. Galvanized or plain sheet steel has medium shielding effectiveness at the lower power line frequencies, while nonferrous materials, as well as steel, are used to attenuate magnetic fields at higher frequencies.

The suitability of a certain metal for a particular shielding application can often be determined by the thickness required to obtain a certain attenuation. By rearranging Equation 12-25, the shield thickness necessary for a given attenuation A (dB) is found to be:

$$t = \frac{A}{3.338 \times 10^{-3}\sqrt{fG\mu}} \text{ mils} \tag{12-31}$$

wherein:

f = frequency in Hertz and should be the lowest frequency for which attenuation A is required

G = the conductivity of the shield relative to copper

μ = the relative permeability of the shield material

If a metal is chosen that does not have proper conductivity and permeability at the chosen frequency, the shield may have to be so thick as to be impractical.

Following is an example: If an absorption loss of 150 dB at a frequency of 150 kHz was desired, would copper be a good shield? By substituting into the above formula it is found that the thickness of the shield would have to be 0.09 inches, which is impractical in most cases. Table 12-3 gives the relative conductivity, relative permeability, and penetration loss for various metals at 150 kHz. However, there are several factors that influence the choice of shielding materials. If cost is the major consideration, steel will almost always be the best choice. If weight is the overriding consideration, aluminum or magnesium may be preferred. For special problems involving contamination or corrosion, even gold or platinum could be chosen.

To aid in determining which material to use for a particular application, several nomographs are given. Figure 12-3 gives the required thickness of shielding material at a known frequency and a given desired absorption loss.

Use the nomogram as follows:

1. Locate the frequency on the f scale and the desired absorption loss on the A scale. Place a straightedge across these points and locate a transfer point on the unmarked scale (Example: A = 2.5 dB, f = 100 kHz).
2. Pivot the straightedge about the transfer point on the unmarked scale to various metals on the $G\mu$ scale. A line connecting the $G\mu$ scale and the transfer point on the unmarked scale will give the required thickness on the t scale (Example: for soft aluminum, t = 3 mils).
3. The absorption loss graph can also be used in reverse of the above order to find the absorption loss for a given thickness of a shield.

Figure 12-4 gives reflection loss of plane waves, which were discussed in the previous section.

Use the nomogram as follows:

1. Locate the point on the G/μ scale for one of the metals listed and the desired frequency.
2. Place the straightedge between the point on the G/μ scale and the desired frequency.
3. Read the plane wave reflection loss from the R_p scale.

Figure 12-5 gives the reflection loss of an electric field at distance r inches away from a shield.

1. Locate a point on the G/μ scale for one of the metals listed. If the metal is not listed, compute G/μ and locate the point on the numerical scale.
2. Locate the distance in inches between the energy source and the shield on the r scale.
3. Place a straightedge between the G/μ scale and r, locate a transfer point on the blank scale.
4. Place a straightedge between the transfer point on the blank scale and the desired frequency on the f scale.
5. Read the reflection loss on the R_e scale.

Metal	Conductivity	Permeability (150 kHz)	Penetration Loss (dB/mil at 150 kHz)
Silver	1.05	1	1.32
Copper	1.00	1	1.29
Gold	0.70	1	1.08
Aluminum	0.61	1	1.01
Magnesium	0.38	1	0.79
Zinc	0.29	1	0.66
Brass	0.26	1	0.66
Cadmium	0.23	1	0.62
Nickel	0.20	1	0.58
Bronze	0.18	1	0.55
Iron	0.17	1,000	16.9
Tin	0.15	1	0.50
Steel (SAE 1045)	0.10	1,000	12.9
Lead	0.08	1	0.36
Hypernick	0.06	80,000	88.5
Monel	0.04	1	0.26
Mu-Metal	0.03	80,000	63.2
Permalloy	0.03	80,000	63.2
Stainless Steel	0.02	1	5.7

TABLE 12-3 CONDUCTIVITY AND PERMEABILITY, RELATIVE TO COPPER, AT 150 kHz

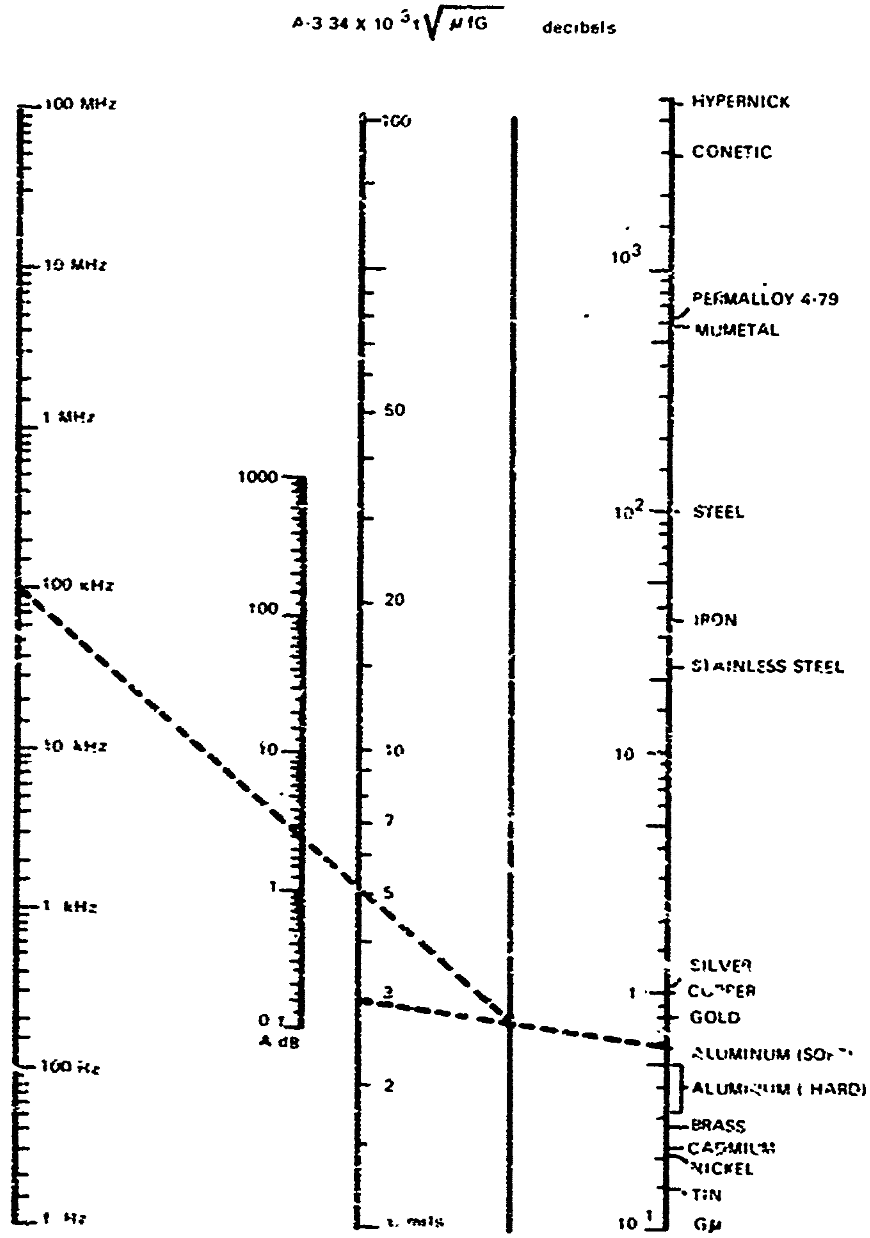


FIGURE 12-3 ABSORPTION LOSS NOMOGRAM

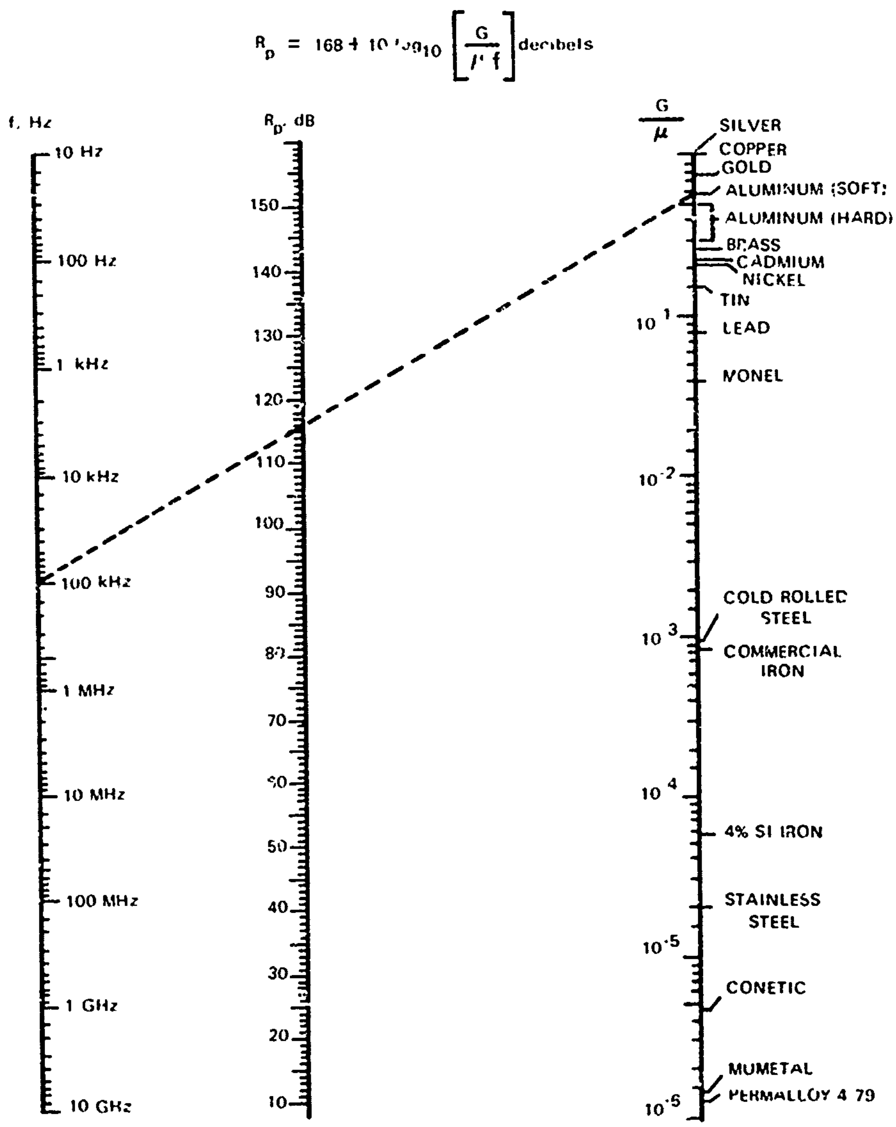


FIGURE 12-4 PLANE WAVE REFLECTION LOSS NOMOGRAM

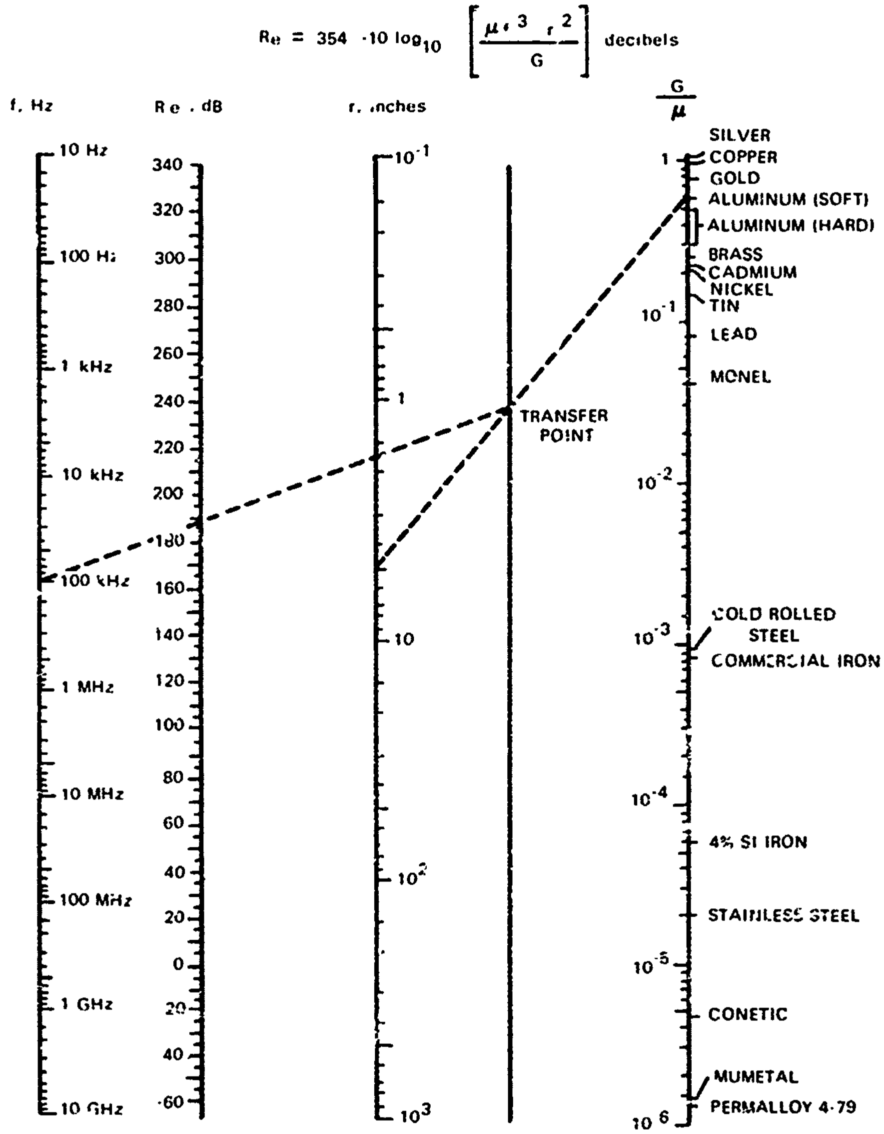


FIGURE 12-5 ELECTRIC FIELD REFLECTION LOSS NOMOGRAM

Figure 12-6 gives the reflection loss for magnetic fields and is found the same way as R_e is found for Figure 12-5.

A practical shielded enclosure may require openings for ventilation. Metal honeycomb panels allow the passage of air into and out of an enclosure while maintaining a desired level of shielding. The shielding effectiveness of honeycomb material is based on the attenuation of waveguide operated below

$$R_h = 20 \log_{10} \left[\frac{0.462}{r} \sqrt{\frac{\mu}{fG}} + 0.136\, r \sqrt{\frac{fG}{\mu}} + 0.354 \right] \text{ decibels}$$

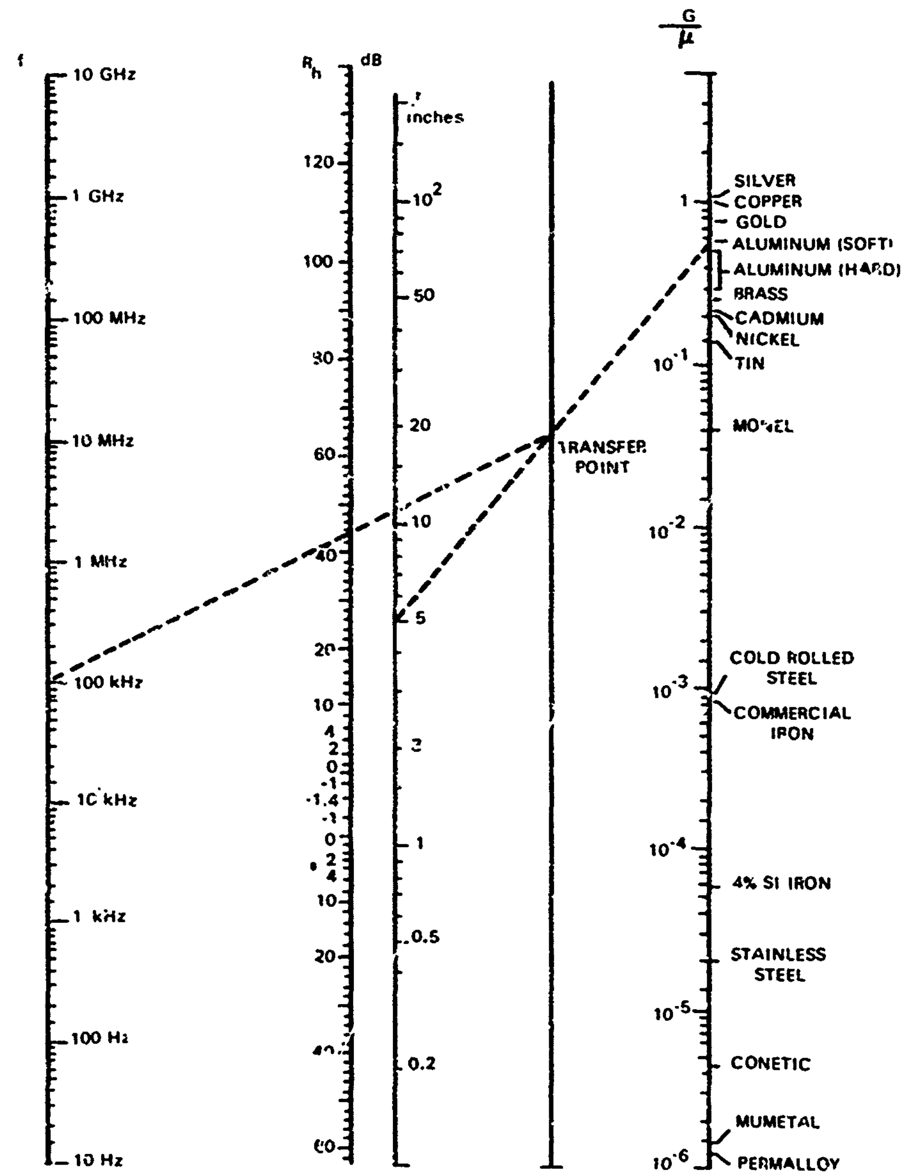


FIGURE 12-6 MAGNETIC FIELD REFLECTION LOSS NOMOGRAM

the cutoff frequency. Cutoff frequency is determined by the effective diameter of a honeycomb cell, and attenuation of the cell is determined by the length of the cell. Honeycomb panel can be obtained with shielding effectiveness on the order of 100 dB for electric and plane wave fields. Magnetic field shielding effectiveness is on the order of 50 dB at 10 kHz. Honeycomb panels for ventilation have several advantages over wire screen: It has a greater attenuation over a specified frequency range, it is not as easily damaged, it is less subject to deterioration by oxidation and exposure due to the type of construction.

Honeycomb (Figure 12-7) has the disadvantage of occupying far greater volume and costing much more than wire mesh. To avoid compromising the effectiveness of the shielded enclosure, the honeycomb must be as effective as the metal panel in which it is installed. Each honeycomb cell wall must be well bonded electrically to the adjacent cell walls. The material used must be consistent with the enclosure shield material; that is, if the shielded enclosure is steel, the honeycomb should be made of similar steel. The honeycomb panel should be completely and well bonded, not just clamped, into its frame. For welded-seam shielded enclosures, the honeycomb panel frame must be continuously welded into the shielded enclosure.

Some shielded enclosures may require a viewing opening or window for the observation of a meter or other display device. Shielded windows are available for this purpose. One type makes use of a knitted wire mesh laminated between two panels of glass or clear plastic. This is made with a metal frame that contacts the wire mesh around the periphery and is bonded to the shielded enclosure. Another type of window is of glass that has a thin electrically conductive metallic coating on one surface. The shielding effectiveness of conductively coated glass is good for electric and plane wave fields but poor for magnetic fields. The complete periphery of the conductive coating must be bonded to the shielded enclosure.

A nonmetallic enclosure may be shielded by coating the enclosure with one of the high conductive lacquers specially formulated for shielding. They are fine silver-based or carbon-based lacquers that adhere to metal, plastic, ceramic, wood, and concrete. When applied to a nonconductive surface, they substantially reduce the surface resistivity. These lacquers are expensive and are not used on large enclosures. Conductive caulking compounds and conductive epoxy cements may also be used to fill irregularities between surfaces that have poor contact or to provide a bond where conventional methods cannot be used.

MEASUREMENT OF SHIELDING EFFECTIVENESS

Calculations to find the shielding effectiveness are based on approximations; it is often desirable to make actual measurements of the attenuation caused by a shield. One method for measuring the attenuation of electromagnetic fields by a shielded enclosure is given in MIL-STD-285.

MIL-STD-285, "Attenuation Measurements for Enclosures, Electromagnetic Shielding, for Electronic Test Purposes, Method of" describes accepted methods of measurement of shielding effectiveness for magnetic, electric,

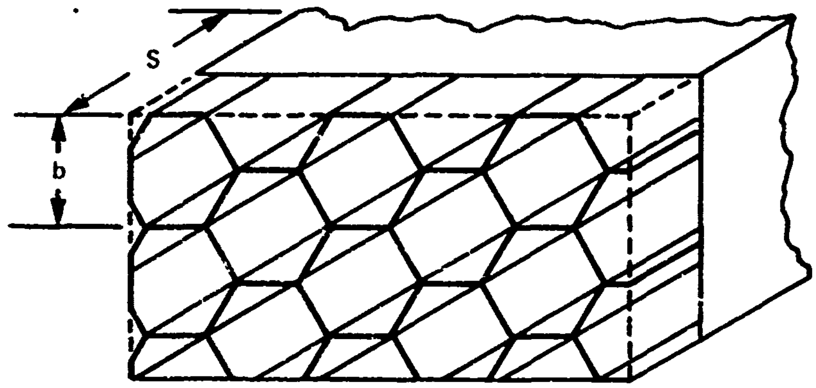


FIGURE 12-7 SECTION OF HONEYCOMB SHIELD

and plane wave fields. Basically, the method uses a signal source on one side of an enclosure wall and a signal-measuring device on the other side of the wall. A reference level is established on the signal measuring device and the enclosure wall is removed. If the enclosure wall cannot be removed, then the signal source and signal measuring device are moved to an open location, maintaining the same relative position. A calibrated attenuator in the signal-measuring device is adjusted until the reference level is again obtained. The difference in attenuator readings represents the attenuation of the shielded enclosure at that particular location on the enclosure wall. As the signal source and signal-measuring device are moved to various positions and as antenna orientation is varied, there will usually be a variation in the attenuation reading. This may be due to openings or cracks in seams between panels or to poorly fitting doors or access panels.

Magnetic field attenuation is measured with single turn loop antennas positioned in the same plane and perpendicular to the enclosure wall. Electric field attenuation measurements are made with rod antennas maintained parallel with each other and oriented in any position parallel to the shielded enclosure wall. Plane wave field attenuation is measured using tuned dipole antennas maintained at a distance of at least two wavelengths from the enclosure wall. The receiving antenna is oriented for maximum indication on the signal measuring device. The tuned dipole antenna must be a balanced dipole. This requires a balun if the antenna is connected to an unbalanced coaxial cable.

It is important to test case leakage of the attenuator and signal measuring device to make sure that the signal measured is actually due to signal pickup by the antenna and that case leakage does not influence the reading. This can be done by disconnecting the antenna and using a shielded cap on the antenna input connector.

Another commonly used test method for finding shielding efficiency is the insertion loss test. This test uses small coplanar loops. The loops have a diameter

of 3 inches, and about 3.5 inches separate the loop centers, if space permits. The electromagnetic field in the plane of the loop causes a current to flow in one direction on the test sample and tests that area with a wave having essentially the impedance of a wave from an infinitesimal point source located at the same distance as the center of the loop. The primary advantages of this method are the ability to test small samples and to minimize the environmental reflection. This method is not applicable for use at low frequencies because of "leakage" coupling around the sample, unless the loops are completely enclosed in a special shielding fixture.

Coaxial loops have been used to test shielding effectiveness, but this method has a number of disadvantages. The field in the direction of the loop axis induces a circular current in the test sample. Impedance ratios vary from point to point on the test samples, making reflections difficult to compute. Tests made with coaxial loops give lower insertion loss readings because of lower wave impedance and, consequently, lower reflection losses.

When the effectiveness of shielding against plane waves is tested, the radiation field is important and, consequently, antennas must be used separated by a considerable distance in comparison to the wavelength involved.

PRACTICAL SHIELDING DESIGN

EQUIPMENT CABINETS

The equipment cabinet designed to act as a shield will only approach the value of shielding effectiveness for the type and thickness of metal of which it is fabricated. All practical shielded enclosures have discontinuities to accommodate functional requirements of the equipment within the case. Figure 12-8 indicates most of the types of discontinuities that the designer must deal with. Each of these problems is discussed below.

1. Seam, no gasket. Clean metal to metal mating surfaces are necessary, together with good pressure contact obtained by the use of clamps, machine screws, or rivets. Corrosion or anodizing cannot be allowed. The effect of screw spacing on shielding effectiveness is shown in Figure 12-9.

2. Seam, metallic gasket. Considerable improvement in shielding effectiveness can be obtained by using a metallic gasket. This type of gasketing is available in a great variety of materials and designs. Some types include provision for use as a moisture barrier in addition to shielding. Clean metal to metal mating surfaces and good pressure contact are still required.

A woven knitted wire mesh type of gasket is manufactured in a variety of sizes and materials. The selection of the type of material should be governed by consideration of the galvanic order of the cabinet metal as well as the gasket metal. The gasketed joint should be designed so that the metallic gasket is compressed enough to provide a continuous low-resistance peripheral contact with the cabinet and the cover plate. At the same time, the gasket must not be

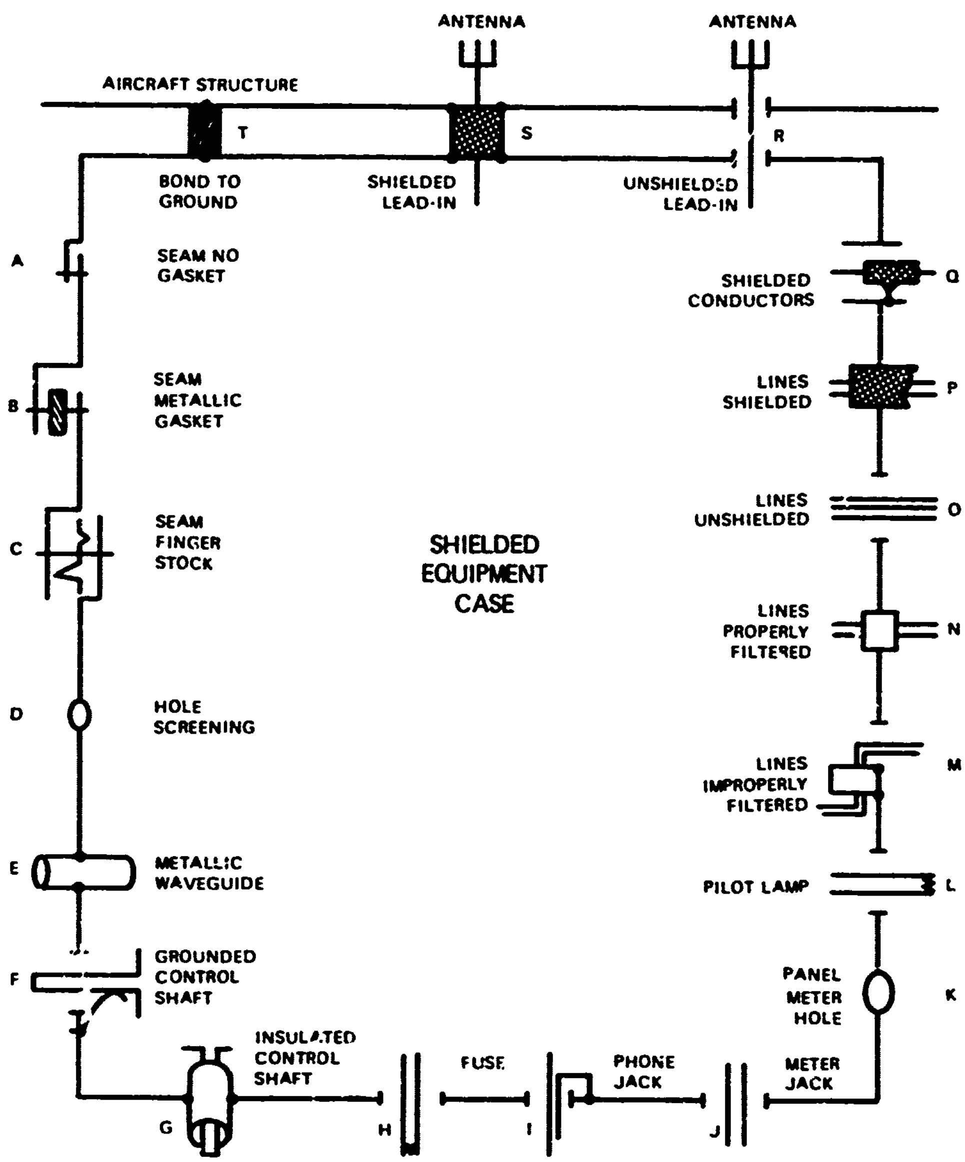


FIGURE 12-8 TYPICAL SHIELDED ENCLOSURE DISCONTINUITIES

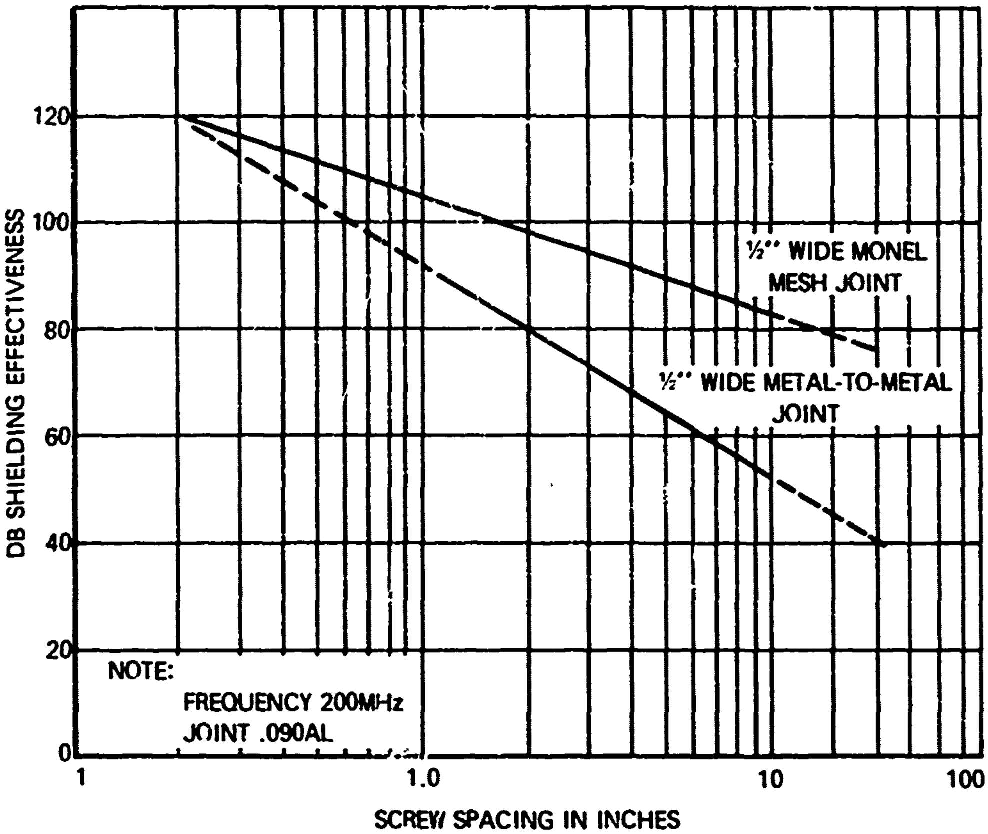


FIGURE 12-9 SHIELDING EFFECTIVENESS VS. SCREW SPACING

compressed beyond its elastic limit. This is usually at about 70 percent of original thickness. Some type of stop must be designed into the joint to limit compression to this value. The width of the gasket is an important factor. A wider gasket will provide better conductivity across the discontinuity.

3. Seam, finger stock. Finger stock is made of beryllium copper, phosphor bronze, or spring brass. It is usually soldered to one of the mating surfaces. When access covers or doors are operated frequently, finger stock has advantages over other types of metallic gasket. It provides a wiping contact that is self cleaning and it does not lose resiliency with each opening and closing of the door or cover. However, it is brittle and individual fingers may break off and require replacement. A well designed seam will protect the tips of the fingers when the door is open or the cover plate is removed.

4. *Holes and screening.* Holes in the case used for ventilation or for any other purpose will materially decrease the shielding effectiveness of the case. The larger the diameter of the hole and the higher the frequency considered, the greater will be the leakage. Holes must be kept as small as possible. If a large hole is covered with wire mesh screen, the screen must be directly bonded to the case around the complete periphery of the opening.

5. *Metallic waveguide.* Leakage through holes can be significantly reduced if the holes are designed as a waveguide with a cut-off frequency higher than the highest frequency to be shielded. A circular waveguide will give 100 dB attenuation when the length is 3 times the diameter of the hole. The cutoff frequency, f_c, is related to the hole diameter as follows:

$$f_c = \frac{6.92}{d} \qquad (12\text{-}32)$$

where d = diameter of waveguide in inches.

The most efficient ventilation system uses waveguides in the form of metallic honeycomb. The diameter of the honeycomb openings determines the highest frequency at which the honeycomb is an effective shield. The depth of the openings will depend upon the degree of shielding that is required. This must be balanced against the number of openings in the honeycomb panel. As the panel is made larger, it will incorporate more openings and its shielding effectiveness will decrease unless the depth of the openings is increased.

6. *Control shaft-grounded.* Metallic control shafts protruding through the equipment case are grounded to the case by a metal gasket or serrated metallic fingers. Any metal protrusions through the panel should be avoided. Toggle switch handles must be well grounded.

7. *Control shaft-insulated.* Control shafts should be made of an insulating material and should penetrate the panel through a waveguide. The waveguide must be well bonded to the panel and it may protrude through the panel or remain flush with the front of the panel.

8. *Fuse receptacle.* A conventional fuse receptacle creates a large hole in the panel that exposes a part of the fused circuit. This brings a possible source of interference to a position where it can radiate to the outside. Special fuse receptacles are available with a metallic screw-on cap that will maintain shielding integrity.

9. *Phone jack.* The phone jack should also be provided with a metallic cap. The phone circuit should be filtered by a low pass filter mounted directly behind the panel and bonded to the panel so that shielding integrity is maintained.

10. *Meter jack.* The meter jack should be provided with a metallic cap and, where required to maintain shielding integrity, a filter should be installed as described for the phone jack.

11. *Panel meter.* Installation of a meter on the panel usually requires a large hole. The meter should be backed with a cup-shaped shield well bonded to the panel. Meter leads should be filtered. This is usually best done with feed-through capacitors. There are meters that can be flush mounted on the exterior of the panel. These require only two small holes for the meter terminals.

12. *Pilot lamp.* Pilot lamps and lighted switches are available from several manufacturers for installation on shielded panels. They are designed to bond

directly to the panel and incorporate some type of screen or perforated metal shielding over the lamp. In extreme cases, it may be necessary to filter the leads.

13. *Lines, improperly filtered.* Lines that are unfiltered or improperly filtered will seriously degrade the shielding effectiveness of the cabinet. A filter is improperly installed if it is possible for the input leads to couple with the output leads due to a lack of shielding between input and output circuits. The filter must have a direct low impedance bond to the shield panel.

14. *Lines, properly filtered.* When the filter is properly installed, it will maintain its filter insertion loss capability and maintain shielding continuity. It must also have sufficient insertion loss to maintain the degree of shielding effectiveness required by the system design. Cable connectors are now available with miniature filters built into each pin. These offer space and weight advantages if their performance characteristics are acceptable.

15. *Lines, unshielded.* Open wiring may provide a medium for excessive leakage into or out of the equipment cabinet. Open wire penetrations can only be tolerated under special circumstances in cabinets that have low requirements for shielding effectiveness.

16. *Lines, shielded.* Shielded conduits or shielded transmission lines must have an outer wall or shield with a shielding effectiveness as good as that of the shielded enclosure itself.

17. *Shielded conductors.* The braid shielding of all such conductors should be carried well within the AN connector wall and grounded to it.

18. *Antenna, unshielded lead-in.* This type of penetration is no longer permitted.

19. *Antenna, shielded lead-in.* The shielding effectiveness of the transmission line must be as good as that of the shielded case, to be effective. Single braid shielded coaxial cables such as RG-8/U have been found to be unsatisfactory and should be replaced with the double braid type such as RG-9/U or RG-214/U.

20. *Bond to ground.* The best designed shielded enclosure, even without any discontinuities, is not a perfect shield. It must be properly bonded through a mounting rack to a common reference ground such as the aircraft structure. A good bond will materially reduce the radiation leaking out of the shielded enclosure. A poorly designed bond will, in addition to increasing the radiation from the case, permit undesired signals in the vicinity of the equipment to appear at the input of a receiver and possibly cause undesired response or malfunctioning.

Any metallic enclosure will have at least one resonant frequency. Most enclosures will have primary and secondary resonant frequencies, which are a function of the major dimensions of the enclosure. There will be additional resonant frequencies due to internal walls and the spacing of major parts. The designer should be aware of this effect and avoid a design where these natural resonant frequencies fall on the operational frequencies of the system.

The natural resonant frequencies of an enclosure can be determined in terms of wavelength as follows:

$$\lambda = \frac{2}{\left[\left(\frac{\ell^2}{2h}\right) + \left(\frac{m^2}{a}\right) + \left(\frac{n^2}{b}\right)\right]^{1/2}} \tag{12-33}$$

where

λ is the wavelength at the resonant frequency
h is the height of the enclosure
a is the width of the enclosure
b is the length of the enclosure
ℓ, m, and n are random integers denoting the major modes of resonance.
All dimensions are in the same units.

In room size enclosures, the primary resonant frequencies may be below 100 MHz, with secondary resonant frequencies extending upward from there. Smaller enclosures will have correspondingly higher resonant frequencies. With careful design, these resonant frequencies can be avoided unless the enclosure contains a broadband source of energy. A broadband energy source will excite the enclosure to the extent that the resonant frequencies can be detected by measurements on the outside of the enclosure.

SHIELDED ROOM DESIGN

The term "screen room" is sometimes used to designate a shielded room. Originally, most shielded rooms were made of copper or bronze wire screen. It was convenient to fit the wire screen to wooden frames that could be readily bolted together on the site. Wire screen is easily punched through by sharp-cornered objects. To maintain a minimum shielding effectiveness in case of punch through, the wire screen was applied to both sides of the wooden frame. This led to the development of two methods of design for the double shielded screen wire shielded rooms.

Figure 12-10 shows diagramatically the single shield type of room with panels bolted together, air vent, power line filter panel, and hinged door. The two types of double shielded rooms are also shown. One type known as the double shield, cell type construction does not isolate the inner from the outer shield. Each panel forms a completely shielded cell. The double shield, isolated type completely isolates inner and outer shields except at one point, at the filter panel. This is also the common point for grounding. This type of design prevents circulating currents from coupling energy between shields at low frequencies. A disadvantage of the double wall shield is that internal reflections between the walls do not cancel. At resonant and anti-resonant frequencies, determined by the interwall spacing, the gain or loss may be as much as 40 dB.

Current practice has abandoned wire screen material for room shielding in favor of solid metal panels. A metal frame is used instead of the wooden frame and the panels are held to the frame with a bolted clamp arrangement. An alternate method uses plywood panels with a metal skin. These panels are clamped together around each edge.

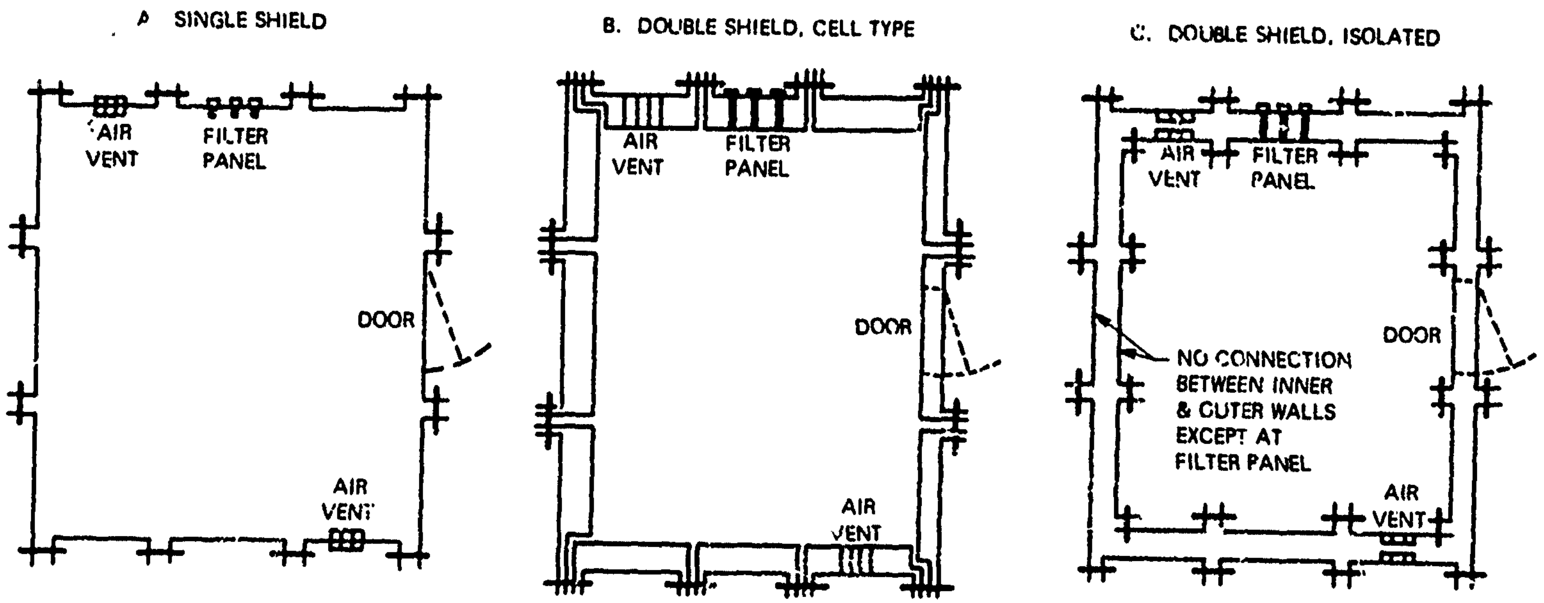


FIGURE 12-10 CONSTRUCTION OF DEMOUNTABLE SHIELDED ENCLOSURES

Equal in importance to the choice of material is the method of making panel seams, doors, vents, and other penetrations permanently effective against intrusion of electromagnetic fields. The difficulties involved in obtaining and permanently maintaining effective shielded seams impose the most severe of all shielded enclosure design problems. Unless there is a completely overriding requirement that the enclosure be easily demountable, all panel seams should be welded with continuous seams and supported by a substantial frame.

Carefully designed and installed bolted clamps for demountable panel seams are equal to welded seams for lighter gauge shielding materials, and the initial cost for small enclosures is usually less for this method. However, regular maintenance is required to approximate the initial effectiveness, and the overall life is limited by eventual irreversible loss of shielding at clamped seams. No seam maintenance is required for well designed and properly installed welded panel seams.

The next most difficult problem is providing door seals that remain effective over long periods of use. Doors that use finger contact strips or metal wire gaskets require considerable costly maintenance. Shielded enclosure doors of very high effectiveness that require no finger contact strips or gaskets are available.

Because of generally more severe shielding requirements, particularly for low frequency magnetic fields and for electromagnetic pulse (EMP) simulation and protection, a class of "high performance" or "extended range" shielded enclosure is coming into wide use. These enclosures have the advantages of virtually unlimited attenuation, permanence, and low maintenance requirements, and are easily fabricated to any specified dimensions.

Figure 12-11 illustrates the typical construction of high performance permanent shielded enclosures of three basic types. The single shield type is most commonly used because any desired metal (usually steel) of any thickness may be used. Because the seams are continuously welded and permanently leak proof, it is not necessary to have the second shield as a back-up to reduce leakage. All the doors illustrated are sliding inflatable doors with no gaskets. This arrangement is usually required to maintain very high magnetic field attentuation at very low frequencies. For less severe low frequency requirements, a conventional hinged door or inflatable hinged door may be effective.

The double-shielded, cell type permanent enclosure is seldom used since there is no advantage in using two shields of the same total thickness in a permanent enclosure, unless the shields are of dissimilar metals. A disadvantage is the increased cost. However, in some instances a double shielded, cell type enclosure results when the effectiveness of an existing permanent enclosure is upgraded by adding a second wall of shielding material.

The double-shielded, isolated, permanent enclosure is used primarily for applications requiring protection against very high intensity pulses with very steep wavefronts, such as occur in EMP simulation or nuclear explosions. In this type of enclosure, the inner shield is completely insulated from the outer shield except at filter entrance panels. Shielded air vents are installed separately in the

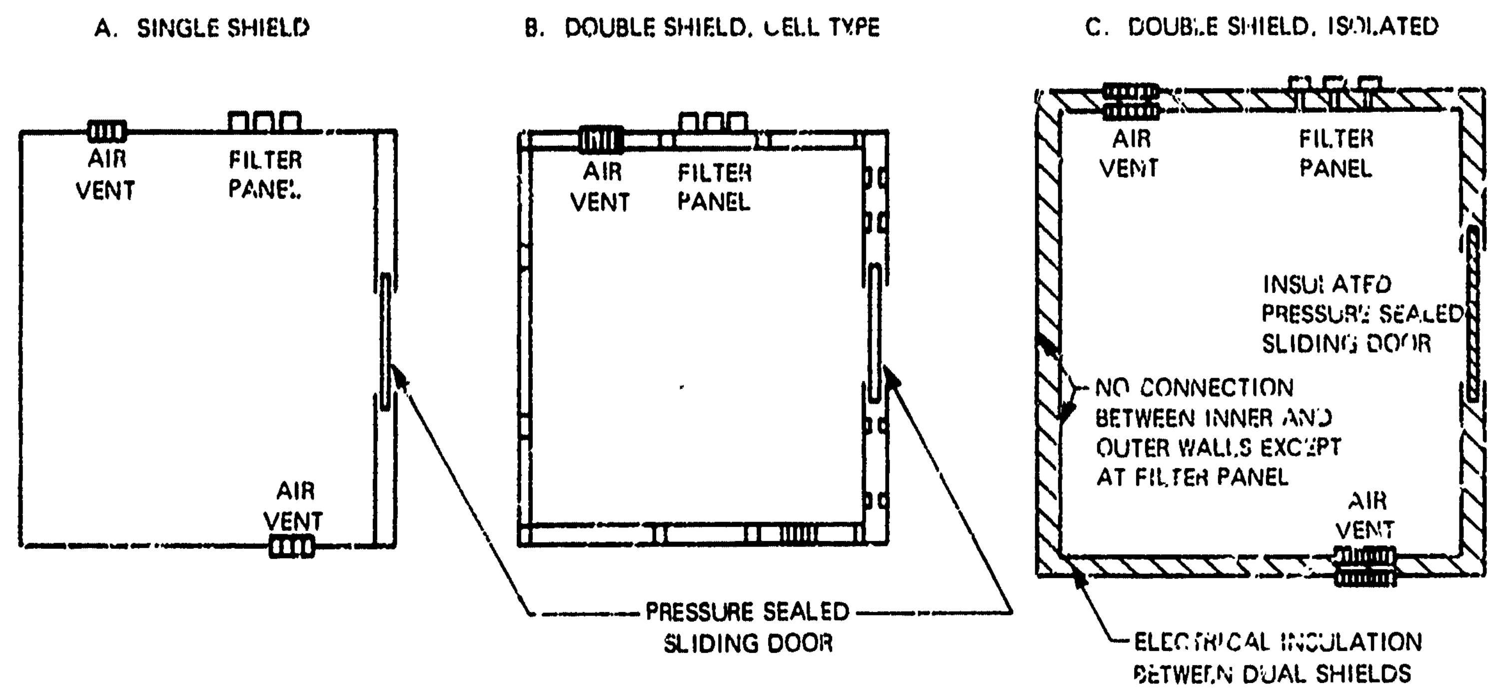


FIGURE 12-11 CONSTRUCTION OF PERMANENT HIGH PERFORMANCE OR EXTENDED RANGE SHIELDED ENCLOSURES

two shields. The door is made of two separate panels separated by electrical insulation.

CONCLUSIONS

The achievement of a given value of shielding effectiveness is most difficult for low impedance low frequency fields of high intensity. The next most difficult design problem is to provide good shielding for high-power microwave plane waves, particularly when the enclosure has many penetrations.

All penetrations of the enclosure, whether for light, ventilation, personnel or equipment access, power and signal leads, or other purposes require special attention in design, fabrication and testing. The degradation of the attenuation below the intact shield wall value due to any specific penetration, can be predicted best on the basis of experience. Theoretical calculation of such degradation does not lead to meaningful results since too many variables of construction are involved.

While achievable attenuation for a given configuration of intact shielding can be predicted, accurate precomputation of the shielding effectiveness of a practical configuration is not currently possible.

Table 12-4 shows practical values of enclosure shielding that may be called for and comments on how they may be obtained. Specification of appropriate values of shielding effectiveness for given applications requires a thorough understanding of the principles of shielding theory summarized in this chapter and discussed in detail in the documents listed in the reference section. In the design of shielded enclosures, consideration should be given to the selection of materials and design factors that will assure that shielding effectiveness will not degrade unduly during the service life of the enclosure. The design must take into full consideration not only shielding requirements but environmental factors including internal and external heat load, ventilation requirements, corrosion, and accessibility for maintenance.

Shielding effectiveness will best be maintained with an effective maintenance schedule. This may include periodic reevaluation of the enclosure by direct measurement of shielding effectiveness or other means. The maintenance schedule should also include such items as inspection of all seams whether welded, soldered, bolted, riveted, or gasketed. Doors and access covers should be examined for warping and damage to latching mechanism. Power and signal line filters should be checked for degradation.

A well designed shielded enclosure that is properly maintained will have a long service life. Shielding is more dependent on good maintenance than any other factor in EMC control.

TABLE 12-4 PRACTICAL VALUES OF ENCLOSURE SHIELDING

0-10 dB - This is very little shielding. An enclosure that reduces an electromagnetic field by this amount is a minimal enclosure. The effect of the shield may be noticeable but other means of isolation may be more practical.

10-30 dB - This represents the minimum range for meaningful shielding. In mild cases, EMI may be eliminated. Shield design is simple.

30-60 dB - This is average shielding required to solve moderate EMI problems. Attention to good shield design is important. RF gasketing is usually required. Measurement of shielding effectiveness in this range is not difficult.

60-90 dB - This is above average shielding used to solve more severe EMI problems. Shield design must give careful attention to details. RF gasket must be used. Measurement of shielding effectiveness requires special instrumentation.

90-120 dB - This is the maximum possible with the best shielding design techniques. Measurements require instrumentation specifically designed for these measurements. In some cases, measurement is beyond present state-of-the-art.

Over 120 dB - Beyond limit of the state-of-the-art, with some specific exceptions, for both shield design and instrumentation.

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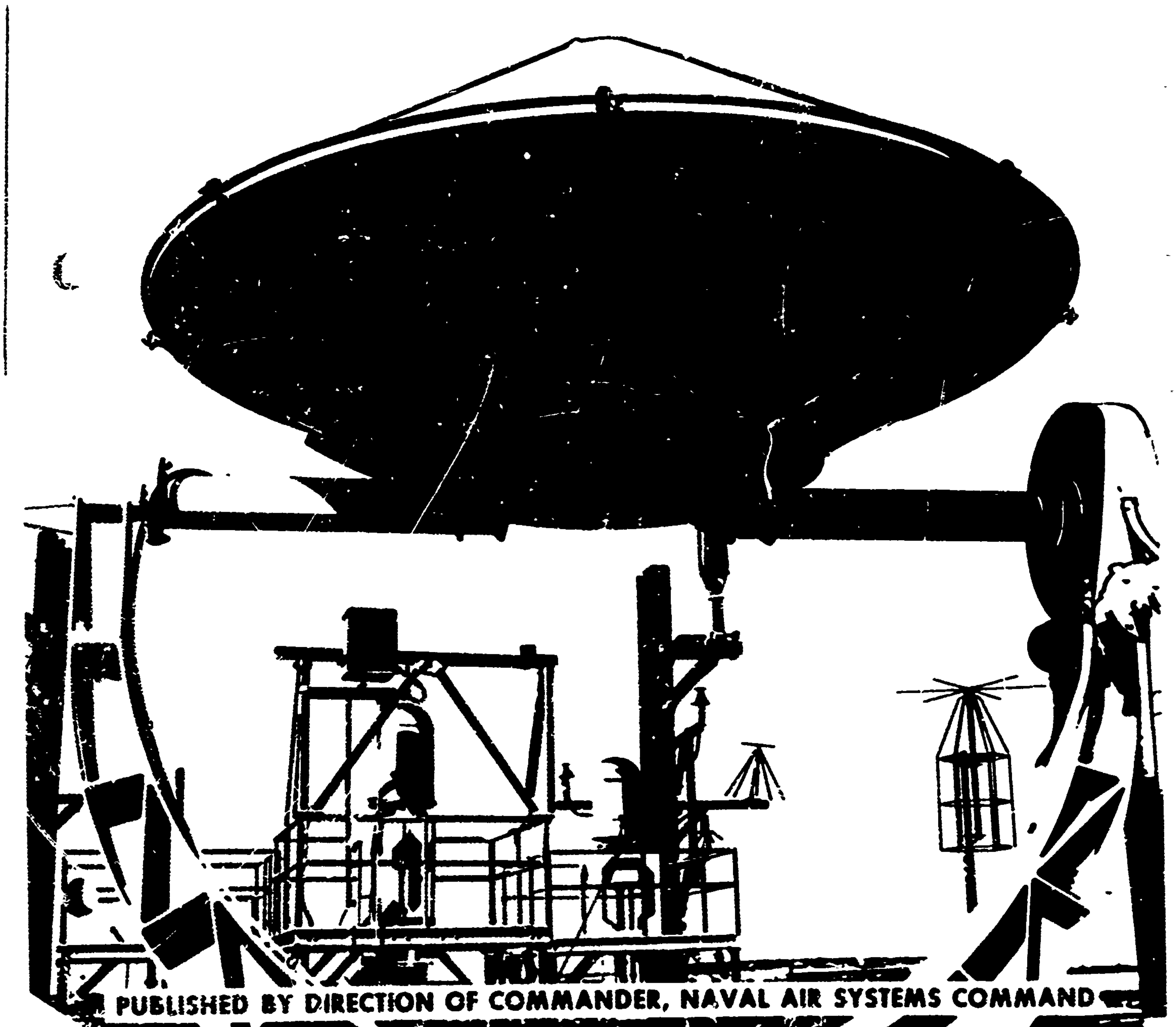
ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 13



CHAPTER 13
WIRING, CABLING, AND CONNECTORS

CONTENTS

ILLUSTRATIONS

INTRODUCTION

In recent years systems have become more complex, incorporating more sensitive devices requiring better isolation. In addition, output devices operate at higher powers and the proliferation of equipment in some aircraft has resulted in its high density. Interequipment wiring has also increased in density and complexity. Consequently, the wiring and cabling installation requires more careful planning to maintain EMC and avoid problems that may be created through coupling of interference into sensitive circuits. Electrical systems have developed in such a manner that interference problems caused by inadequately protected wiring have increased in complexity and in frequency of occurrence.

Routing of wires and cables within modern aircraft is no longer the simple matter of using the shortest least complicated path. Connectors are no longer simply a device for convenient wire to chassis connections. In modern technology, wires, cables, and connectors actually become an electrical subsystem which must conform with the overall design philosophy.

CLASSIFICATION OF CABLES

Interference control is one of the factors to be considered in aerospace system design. One of the most effective ways of reducing the interaction of one cable upon another is to separate them. As the distance between cables is increased, the attenuation of the interference fields becomes greater. Because there is insufficient room in an aircraft to keep each critical wire separated from all other wiring, design philosophy calls for wires and cables to be divided into classes, with each class bundled together and separated from the other classes.

From the EMC viewpoint, wires and cables can be generally grouped into three broad classes:

1. EMI source wires and cables,
2. EMI-sensitive wires and cables, and
3. those wires and cables that are neither sources nor victims (passive cables).

The broad general classes are further divided into more detailed categories as suggested in the discussion of cable installation, Chapter 16.

EMI source cables include radar modulation pulse cables, transmitting antenna cables, and power and control cables that emit interfering electrical or magnetic fields. *Sensitive cables* include radio receiving cables, electroexplosive wiring, audio distribution cables, servomechanism input cables, and all wiring associated with devices susceptible to interference. *Passive cables* include those power and lighting cables, electrical control cables, indicator circuits, and other cables that are neither sources of EMI nor sensitive to it.

Cables in one class should be separated from those of another class. Cables of a higher signal level will tend to introduce interference into cables of a lower signal level. Radar modulation pulse cables should, wherever practicable, be separated by a maximum distance from all other active cables as well as sensitive and passive cables. This physical separation should be maintained even to their point of entrance to the modulator and transmitter. These modulating pulse cables carry extremely high power extending over a frequency spectrum from the pulse repetition rate upwards.

Active cables other than radar modulator pulse cables should be separated 18 inches from all sensitive and passive cables. Sensitive cables should be separated by at least 2 inches from passive cables.

SUSCEPTIBILITY OF CABLES

There are several mechanisms by which a cable can pick up interfering energy from another cable.

Magnetic coupling is a common producer of interference coupling. Magnetic coupling introduces interference signals by mutual inductance between two wires. The amount of signal coupled depends upon the current in the interfering cable, length of the susceptible cable, frequency of the interference

signal, and the distance between the two cables. The contribution of magnetic coupling to cable interference is most noticeable when the circuitry attached to the cable operates into low impedances at both ends.

Perhaps the most obvious way to reduce magnetic coupling is through physical separation of interference source circuits from susceptible circuits. This reduces the induced voltage by lowering the flux density in the susceptible cable. The induced voltage drops exponentially with the wire separation.

Another means of reducing the induced voltage is to reduce source or loop areas. The area of the loop is the area enclosed by the supply and return wires of a circuit. This method is very effective in reducing magnetic coupling but it is often neglected. If a current-carrying wire and its return current are immediately adjacent to each other, the loop area is effectively made very small. The accomplishment of this objective is often a complex problem in large systems due to noncontiguous loads and equipment grounding practices. Twisted pair wire effectively reduces the source loop area by setting up equal and opposite self-cancelling voltages in the susceptible cable.

Twisted pair, at low frequencies, can be more effective than shielding. The effectiveness of twisted pair of twisted triads becomes less as frequency increases, but it continues to be useful even at RF, especially if augmented by shielding. By transposing conductors carrying current in opposite directions, equal and opposite EMI fields are linearly coupled to adjacent conductors. The effectiveness of field cancellation depends upon current balance in the conductors and upon the pitch of the twists.

Two circuits can also be isolated, to some degree, by the use of shielding. Shielding can be provided by either high conductivity or high permeability materials. Below about 5 kHz, ferrous shielding is used. At these low frequencies, high conductivity shields would have to be very thick to provide effective shielding. Ordinary copper braid shielding provides practically no magnetic shielding at these frequencies. High conductivity shields become more effective at higher frequencies. Copper braid has a shielding effectiveness of less than 10 dB up to 20 kHz, but it increases to 40 dB at 1 MHz and up to 100 dB at 40 MHz.

When two cables intersect, crossing them at right angles to each other reduces the amount of coupling between them.

Electric coupling also occurs in wiring due to distributed mutual capacitance. In long cable runs, an appreciable capacitance is likely to exist between adjacent wires and from each wire to ground or shield. Additional capacitance will exist at connectors and associated wiring.

Electric coupling between cables can be reduced by the following steps:

1. coupling capacity between cables can be decreased by shielding, or by increasing the spacing between cables;
2. the bypass capacitance to ground of sensitive wires can be increased to the degree consistent with circuit performance;
3. a lower input impedance can be used in the susceptible terminating device;
4. balanced lines and circuits can be used.

Step 1. can be accomplished by maintaining separation between the cables over as much of the run as possible, by crossing the cables at right angles to each other, and by similar means. The use of shielding on either wire will greatly reduce the amount of coupling between them. For low frequency electric coupling, the shield should be grounded at one end only. Full advantage should be taken of the inherent shielding effect of installed cable trays, stiffeners, and other structural members.

Step 2. can be accomplished through proper wiring techniques as well as circuit design. By routing wiring next to a ground plane, the bypass capacitance is increased and the mutual capacitance is decreased. Shielded wire increases the bypass capacitance while reducing the coupling capacitance.

Step 3. is very effective in reducing electric coupling, if it can be accommodated by circuit design. With present-day semiconductor circuitry, it is often the most effective approach.

Step 4. is an effective practice in which both wires of a sensitive equipment connection are maintained at equal but opposite potential with respect to ground. In this situation, the coupled interference voltage appears at points of opposite potential in the input terminal of the terminating device, and its effect is cancelled out, if perfect balance is maintained in the wiring and the interference signal does not drive circuits into nonlinear response regions.

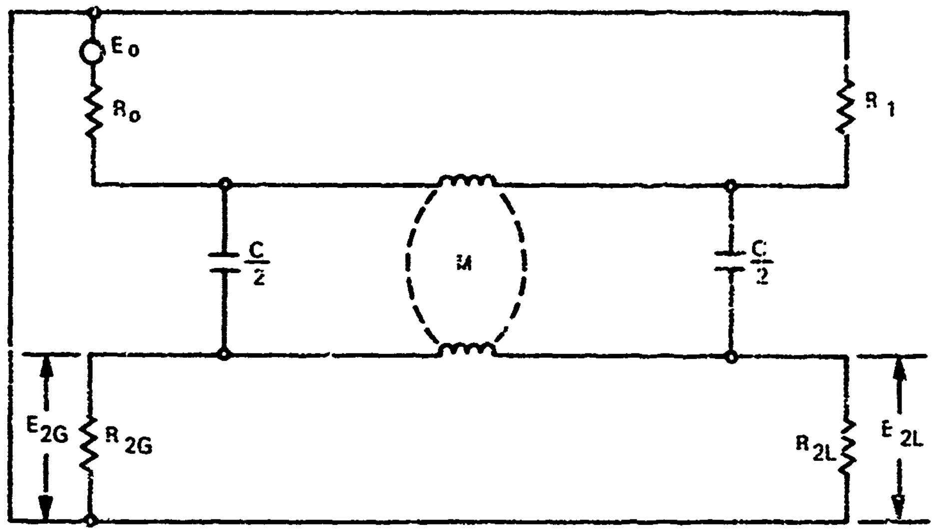
Coupling due to radiation will vary considerably with circuit configuration and frequency. Generally, the coupling increases as the frequency increases, and the efficiency of the sensitive wire as an antenna increases as its length approaches one-half wavelength of the interfering signal. In a coaxial cable, leakage may take place through the braid of the shield. Penetration also occurs because of the finite resistivity of the shield. Shielding used to protect against radiated magnetic coupling should be of high permeability and of sufficient density to maintain flux levels that are below saturation.

CABLE COUPLING PHENOMENA

HIGH-LOW FREQUENCY CONSIDERATIONS

At relatively low frequencies, the effects due to magnetic and electric coupling can be combined and represented in an equivalent circuit such as that in Figure 13-1. The cable coupling in terms of voltage ratio is given below the illustrated circuit. At high frequencies, standing waves become more significant and the equivalent circuit becomes much more complex.

If only linear elements and small levels of coupling are considered, the voltage coupled in electrically and the voltage coupled in magnetically can be calculated separately and added to get the total coupled-in voltage. The calculation and addition must be in terms of complex numbers.



ELECTRIC COMPONENT | MAGNETIC COMPONENT

$$\frac{E_{2G}}{E_o} = \left[\frac{R_1}{R_1 + R_o} \times \frac{R_2}{X_c}\right] + \left[\frac{X_M}{R_1 + R_o} \times \frac{R_{2G}}{R_{2G} + R_{2L}}\right] = K_G^f$$

$$\frac{E_{2L}}{E_c} = \left[\frac{R_1}{R_1 + R_o} \times \frac{R_2}{X_c}\right] - \left[\frac{X_M}{R_1 + R_o} \times \frac{R_{2L}}{R_{2G} + R_{2L}}\right] = K_L^f$$

$$R_2 = \frac{R_{2L} \, R_{2G}}{R_{2L} + R_{2G}}$$

X_M = REACTIVE COMPONENT OF INDUCTIVE COUPLING

X_C = REACTIVE COMPONENT OF CAPACITIVE COUPLING

FIGURE 13-1 CIRCUIT AND EQUATIONS REPRESENTING ELECTRIC COUPLING AND MAGNETIC COUPLING BETWEEN PARALLEL WIRES.

It should be noted from the formula in Figure 13-1 that, at the generating end of the susceptible circuit, the coupled voltage is the sum of the electric and magnetic components; at the load end of the circuit, the coupled voltage is the difference of the electric and magnetic components. The two components of the coupled voltage at the load end can be considered to be in phase opposition. In interference analysis, rather than depend upon a difference voltage, the larger of the two components is assumed to be the coupled-in interference. It is common to assume that as frequency increases, voltage transfer is proportional until unity transfer is reached, and then the transfer is approximated at unity for all higher frequencies. For a considerable variation in loading above or below 300 ohms, $K_G \geqq 2K_L$.

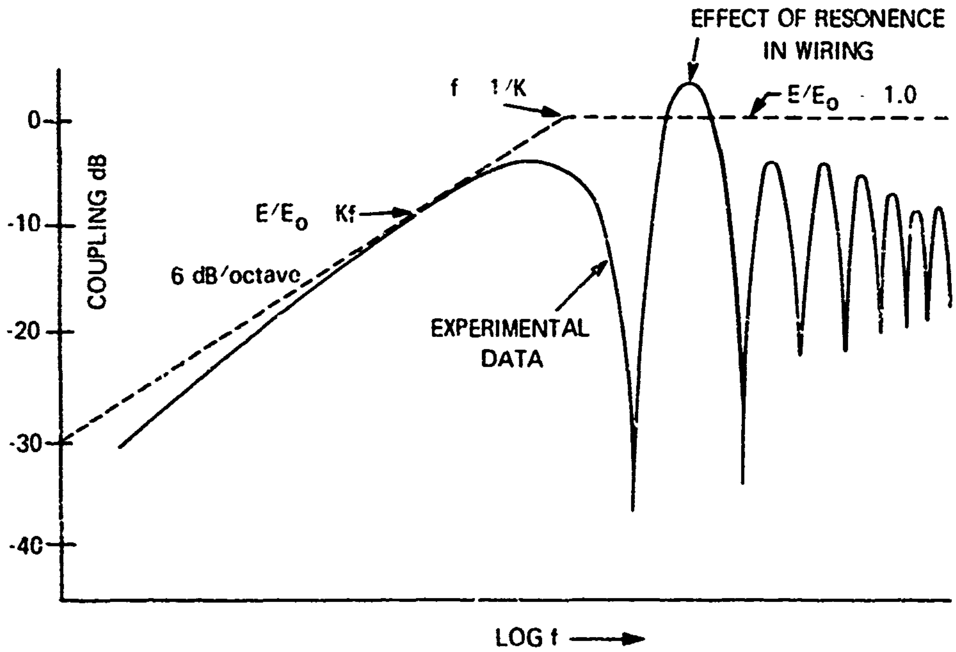


FIGURE 13-2 APPROXIMATE SIGNAL COUPLING IN WIRING

Figure 13-2 shows a plot of the approximate voltage transfer ratio of 6 dB/octave rise to unity. Typical experimental data are plotted with the approximation. The figure shows that the approximation results in a slightly higher coupled-in interference than is shown by experimental data. This is the usual situation; however, with light circuit loading, resonances in the wiring may cause the experimental data to rise above the approximation in a narrow frequency band.

The electric and magnetic coupling components may be determined with the aid of the following formulas for the capacitance and mutual inductance

between wires above a ground plane. The capacitance is given by:

$$C = \frac{(7.35 \times 10^{-12})(\ell)\left[\log\left(\frac{S_{12}}{D}\right)\right]\left[K_{eff}\right]}{\left[\log\left(\frac{4h}{d}\cdot\frac{1}{\sqrt{2-\sqrt{d/D}}}\right)\right]^2 - \left[\log\frac{S_{12}}{D}\right]^2} \text{ in Farads} \qquad (13\text{-}1)$$

The mutual inductance is given by:

$$M = (1.405 \times 10^{-7})(\ell)\left(\log\frac{S_{12}}{D}\right) \text{ Henries.} \qquad (13\text{-}2)$$

The terms used in these equations are:

$$K_{eff} = K_0 + \frac{\left(\frac{d_i}{d}\right)^2 - 1}{\frac{1}{2}\left(\frac{d_i}{d}+\frac{D}{d}\right)^2 - 1}(K_i - K_0) \qquad S_{12} = \sqrt{D^2 + 4h^2}$$

- ℓ = length of the wires in feet
- D = separation of the wires in inches
- h = height above the ground plane in inches
- d = diameter of the wire conductor in inches
- d_i = diameter, in inches, of the wire including insulation
- K_0 = relative dielectric constant of air ($K_0=1$)
- K_i = relative dielectric constant of the wire insulation

The factor $\frac{1}{\sqrt{2-\sqrt{d/D}}}$ in the capacitance equation was determined experimentally.

DESIGN CONSIDERATIONS FOR CONNECTORS

Cable connectors may present interference problems if the system as a whole is not taken into account during the design stages. The connectors are the interface between subsystems and must be selected by agreement among the designers of the subsystems involved. Consideration must be given and agreement reached on such design items as:

1. assignment of leads to connector pins.
2. assignment of shields to connector pins.
3. requirement for coaxial connector pins in the connector for coaxial type cable.
4. requirement for shielding integrity in connector.

5. method of grounding connector.
6. provision for isolating shields if required.

When the designers agree on these items there is little likelihood of incompatibility at the connectors.

Care must be taken to insure that a connector is not an entrance point for interference. Not all connectors are designed to preclude the entry of RF energy. Some do not have a backshell designed to provide a complete shield for the connector. Some connectors incorporate several threaded rings that thread together to clamp the cable jacket, cable shield, and lock the connector body to the chassis receptacle. Each connector surface represents an impedance discontinuity of the cable shield. Figure 13-3 shows a typical connector of this type. The illustration is of a multipin type connector, a standard type of connector for shielded cable. It is important to maintain good clean metal-to-metal surface contact through this connector. The braided shield must be prepared with no trace of jacket material residue or corrosion before assembly. Foreign material at the shield-to-connector interface will allow undue leakage of RF energy through this juncture. It will also present a discontinuity to RF currents on the shield. This will insert an unwanted impedance in the shield circuit. In addition, the coupling that holds the connector to the receptacle must be free of oil film and grit. This is also true in the cable shield circuit where low RF-impedance and shield integrity must be maintained. A good connector is one in which the shielding effectiveness of the mated connector equals or exceeds that of an equal length of shielded cable used in the circuit. In a properly terminated shield, the entire periphery of the shield at the cable and at the connector is grounded to a low impedance reference, minimizing any RF potentials at the surface of the termination. The use of epoxy or other synthetic conducting material is unacceptable for bonding in this situation.

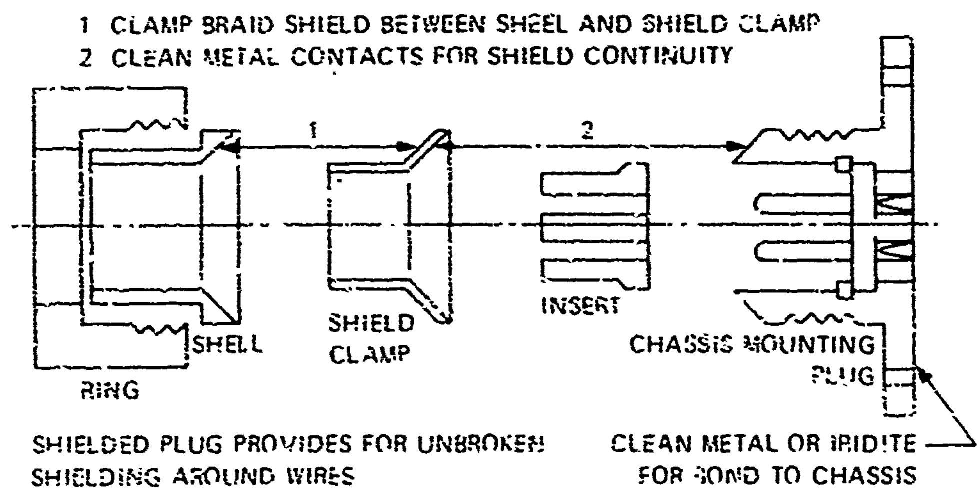


FIGURE 13-3 CONNECTOR DETAIL

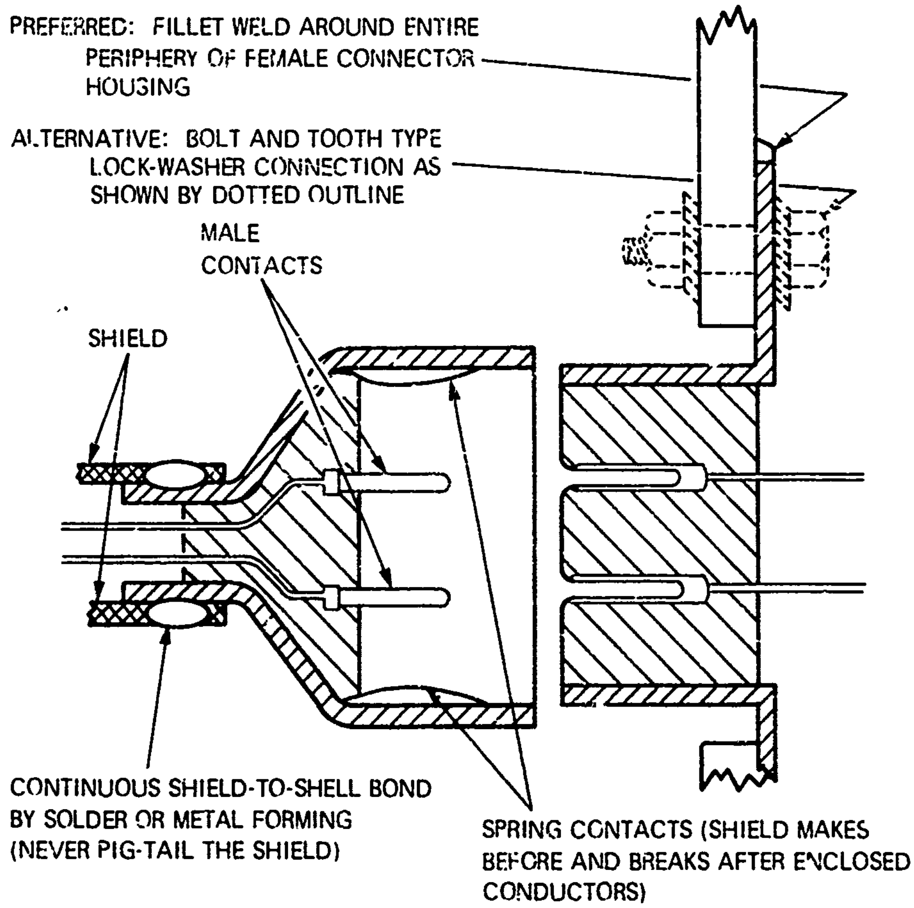


FIGURE 13-4 SHIELD TERMINATION FOR ELECTRICAL CONNECTORS

Figure 13-4 illustrates cable shield-to-connector termination. Figure 13-5 illustrates the method of preserving individual conductor shielding when more than one conductor must be routed through a single cable and connector. The shield should never be pig-tailed and then bonded to the connector; no portion of the shield should be broken before it is bonded to the connector shell. Individual shields for connectors that are routed through multipin coaxial connectors should be terminated individually in the manner above. To keep RF energy from entering sensitive circuits at connector interfaces, the following features should be considered:

1. There should be no break in the shield as the circuit goes through the connector to enable RF energy to leak into the circuit.
2. The connector should be able to withstand environmental conditions (vibration, extreme temperatures, corrosion, etc.) without degradation of the shielding characteristics of the connector.

3. The connector shield at the interface of the two connector halves must make positive contact before the circuit contacts mate and must maintain this contact until after the circuit contacts break.
4. The contacts of the connector mating sections should be sufficiently isolated to preclude the possibility that field personnel will accidently get a shock by touching the socket contacts, either with their fingers or with the mating connector shell while the connectors are unmated.
5. Power and signal circuits should not be routed through the same connector. If they must be routed through the same connector, a barrier of grounded pins should surround the sensitive wire. Power and signal wires should be separated as much as possible in the connector.
6. The input and output signal circuits should not be routed through the same connector.

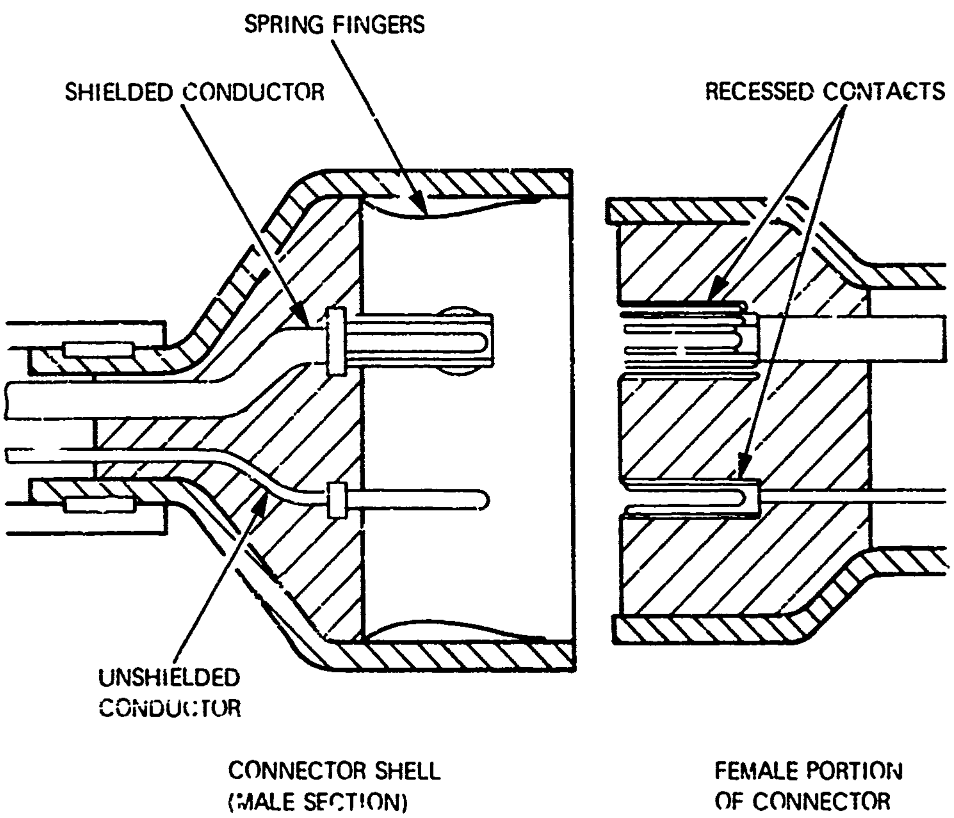


FIGURE 13-5 MULTICONDUCTOR CONNECTOR DESIGN TO PRESERVE INDIVIDUAL CONDUCTOR SHIELDING

TRANSMISSION LINES

A transmission line is an arrangement of electrical conductors by which electromagnetic energy is conveyed from one place to another over a distance comparable with the signal wavelength. Transmission lines provide a link between circuit theory and field theory of electromagentic waves because they can be pictured either as filters with an infinite number of elements or as a pair of conducting surfaces that guide electromagnetic waves between them. They differ from simple electrical circuits in that their L, R, and C are distributed all along the line rather than lumped together at a single point.

If the transmission line were infinitely long or terminated with an impedance equal to its characteristic impedance, the only signal appearing on the line would be the incident wave. Otherwise part of the incident wave will be reflected and the total signal appearing on the line will be the vector sum of the incident and reflected waves. The characteristic impedance of a transmission line varies according to the configuration of the conductor. The equations for determining characteristic impedance of some common types of transmission lines are given in Figure 13-6. The characteristic impedance of other types of lines can be found in electrical engineering handbooks.

The parallel-wire transmission line may consist of two wires or more depending primarily on the power handling capacity required. Corona effect is the most important power limiting factor for the parallel-wire transmission line, while arcing is the most important power limiting factor for coaxial lines, particularly for pulsed signals. These factors are important, due to the possibility of direct coupling to nearby subsystems. In parallel open-wire lines operating over reasonable distances, the possibility of objectionable direct coupling decreases as the number of wires employed increases. In general, parallel-wire lines exhibit less loss than equivalent coaxial lines.

Corona effects and attenuation per unit length at a given frequency are of particular interest in interference considerations. Higher order harmonics and other spurious signals are not attenuated at the same rate. Braided-shield coaxial lines radiate more readily through the shield as the frequency increases. If this leakage is low, however, the inherent low-pass characteristics can be used to good advantage for the attenuation of harmonics. Use of a double-shielded cable instead of a single shield of the same construction, can yield above 1 MHz, an improvement of 25 dB. In braided shielded cable, the leakage field is not always symetrical about the coaxial line.

Coaxial lines using solid copper outer shield or copper clad convoluted steel are also available. These types have a limited flexibility with negligible leakage radiation. Rigid copper and aluminum lines are also available in large diameters for high power transmission.

Transmission line interference can be reduced by correct matching of the load impedance to the characteristic impedance of the transmission line.

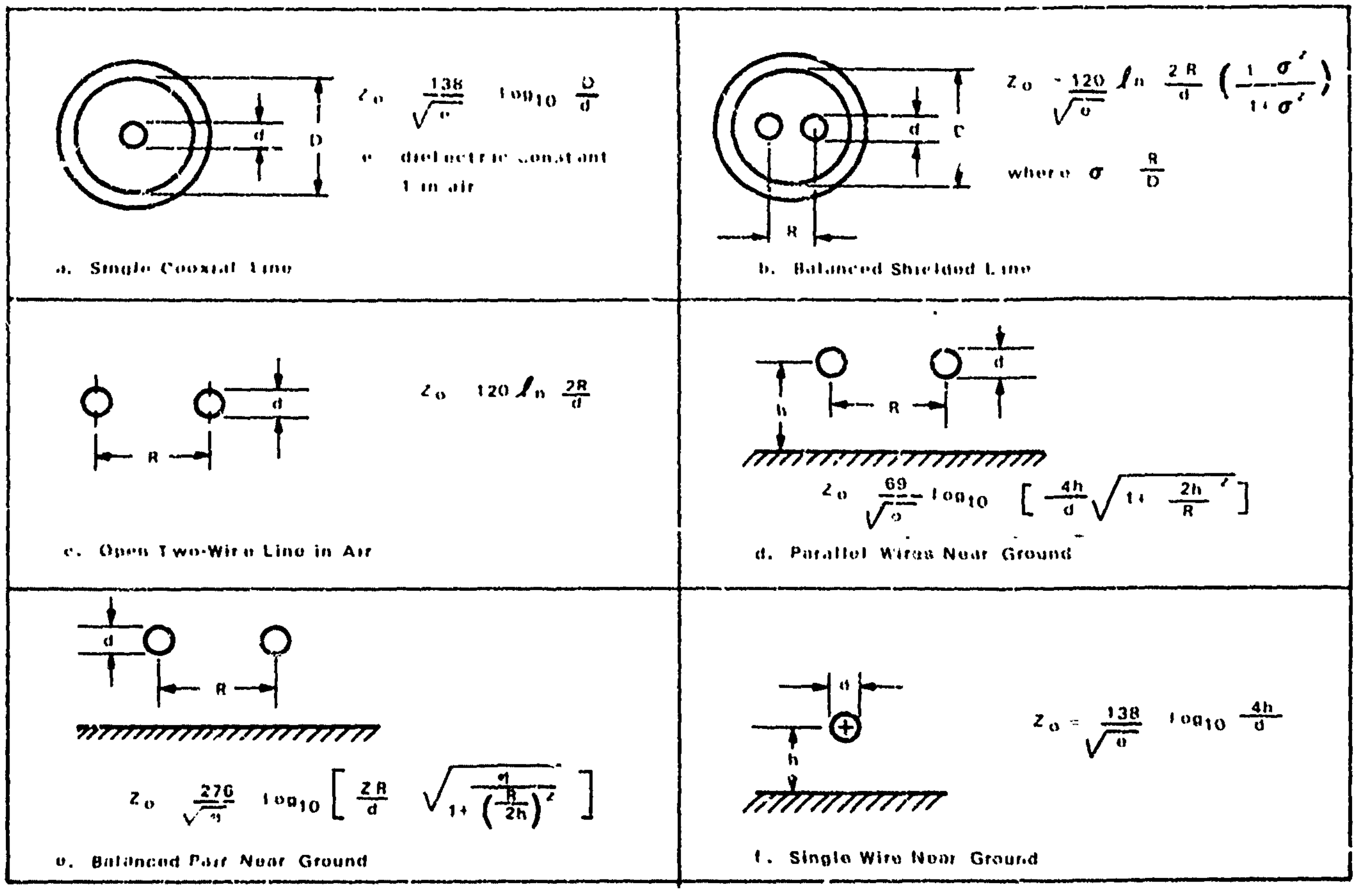


FIGURE 13-6 FORMULAS FOR CHARACTERISTIC IMPEDANCE OF COMMON TYPES OF TRANSMISSION LINES.

When designing a transmission line system, three basic factors should be taken into account:

1. What devices are susceptible to either steady-state or transient transmission line effects? This evaluation covers the frequency spectra of normal signals, transients, and also those frequencies over which interference and interaction spectra extend. After the susceptible devices have been isolated, it is necessary to tabulate tolerable threshold levels. The specific parameters are voltage standing wave ratio (VSWR), phase shift, propagation delay, and reflections.
2. What interference and noise signals are inserted into the transmission lines?
3. Does the transmission line modify the interference signals so that further degradation occurs?

The amount of noise guided and conducted by power transmission lines may be greatly reduced by wrapping the conductor with a thin metallic tape of high permeability. Skin effect losses are greatly magnified by coating the conductor with a thin layer of high-permeability material. The effect of the coating is large in the range of 25 kHz to 50 MHz.

Special coax is available for use in treating severe radiation and leakage problems such as those encountered in high-power pulse applications. Triple-shielded coax should be used where pulse generators are separate from the transmitter or other load. To obtain maximum performance from triple-shielded coax, the terminal ends should be designed to take advantage of the three shields.

Electromagnetic energy can propagate through a hollow metallic tube or waveguide with many possible configurations of electric and magnetic fields; each specific configuration is known as a mode. The particular mode transmitted within a waveguide depends on the exitation employed and on the size and shape of the waveguide cross section in relation to the wavelength or frequency of the wave. Modes are classified in reference to the field components in the direction of energy propagation.

The modes are identified as follows:

TE - Transverse electric mode
TM - Transverse magnetic mode
HEM - Hybrid electric magnetic mode

Modes are further identified by two numerical subscripts that denote the number of half-wave field variations in the width and height dimensions of the guide. For most applications, the dimensions are chosen so that only the dominant mode, that is, the lowest frequency or longest wavelength, will propagate. Standard waveguide uses a width-to-height ratio of 2.

Propagation cannot occur if the spacing between parallel conducting plates is less than half of the cutoff wavelength, λ_c. For an air-filled waveguide,

$$\lambda_c = 2a$$

where a is the greatest dimension of the waveguide rectangular opening. Both wavelength and waveguide dimension may be in inches or centimeters. Thus a waveguide is an effective high pass filter.

The attenuation in a waveguide can be separated into conductor and dielectric losses. For a gaseous-filled guide, the latter may be neglected except at millimeter wavelengths where absorption phenomena take place at certain frequencies. The conductor or wall losses for a given cross section vary as the square root of the resistivity of the material, and the ratio of applied signal wavelength to cutoff wavelength.

The power handling capability of a waveguide is determined by the breakdown on the gaseous dielectric in the vicinity of maximum stress. The gaseous discharge process is to produce ionizing collisions, the buildup of a positive-ion space charge, and finally the creation of sufficient electrons to permit a gaseous discharge. Breakdown is a primary concern under pulsed conditions because the continuous wave (CW) power available from tubes is below the capacity of the waveguide. While heating occurs due to resistive losses in the walls, this is not sufficient to be a limiting factor in power handling capacity.

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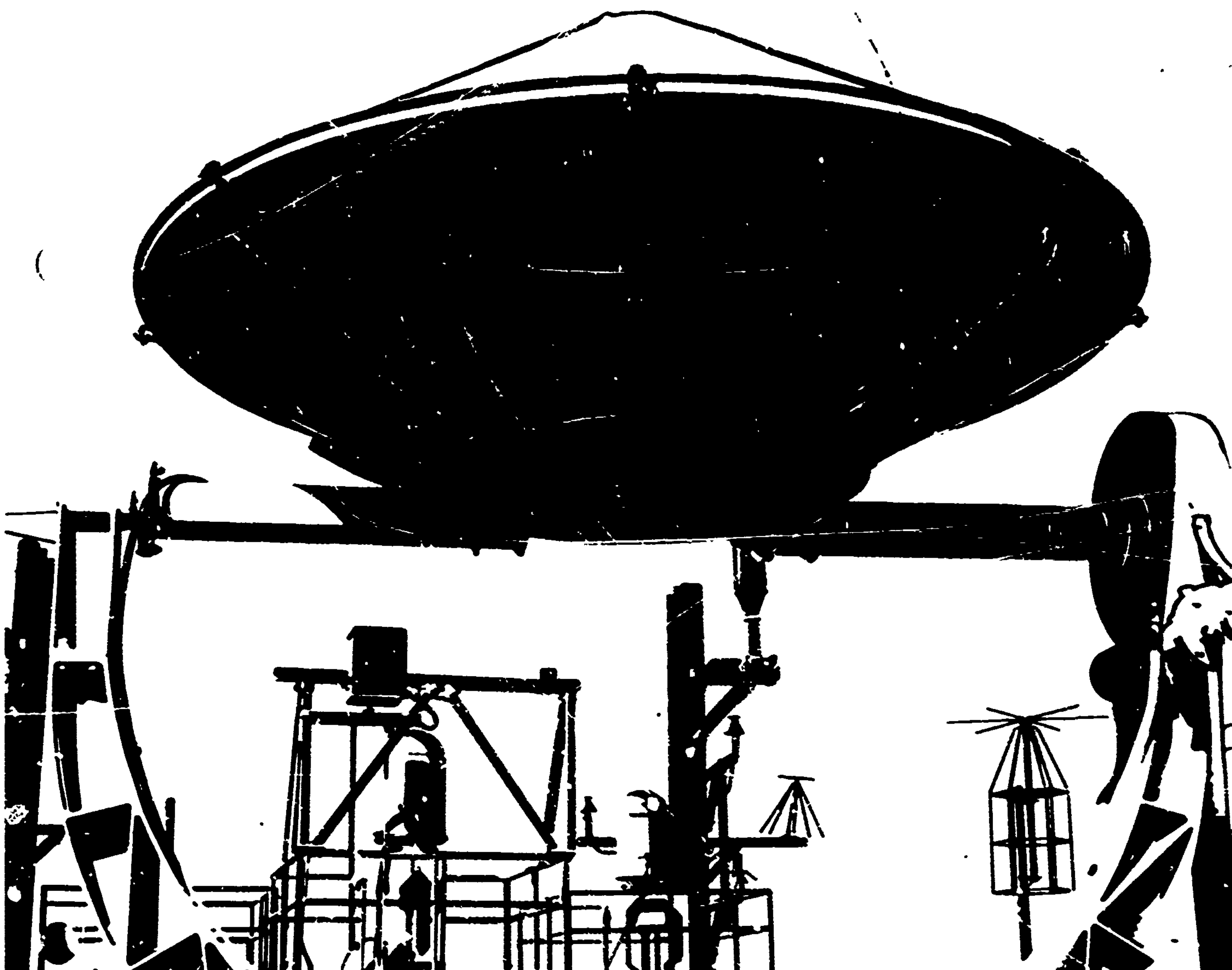
CHAPTER 14



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CHAPTER 14
FILTER DESIGN AND APPLICATION

CONTENTS

ILLUSTRATIONS

NEED FOR FILTERS

Interference is inherent in some electrical, mechanical, and electronic systems. Even when a system has been well designed and provides proper grounding and shielding, the wiring can still conduct unwanted energy into or out of other areas. Filters stop this unwanted energy before it can be conducted to susceptible units to appear as interference. Because of this, filters play a necessary role in achieving electromagnetic compatibility.

Switch noise is a good example of interference for which filtering may be required. Consider a circuit with an inductive load. When an inductive circuit is broken by opening a switch, a back electromotive force is produced by the collapsing magnetic field. This potential rises rapidly in amplitude until an arc occurs across the switch contact. Because the arc is of low impedance, the potential falls until the arc is extinguished, at which time the potential begins to rise again until an arc strikes a second time. This action occurs as the switch contacts travel apart and takes place in a microsecond of time. The arc produces a broad band of interference, which is radiated and conducted away from the switch. Shielding will attentuate the radiated interference at the switch, but filtering will be required to reduce conduction of the noise generated by the arc and possible further radiation. Interference-reduction filters are the primary method by which extraneous energy and interference voltages are isolated from areas where they may prove detrimental.

While filters are necessary and should be placed where needed, care should be taken to avoid using redundant filtering to solve problems caused by uncoordinated efforts of separate design groups. Redundancy usually occurs when each "black box" is required to meet an interference control specification regardless of its cable tie location or its final installation location. Economy measures, the use of equipment of older design in a new system, and schedule constraints can also result in redundant filtering. Although trade-offs must be made among these factors, there is no substitute for a well thought-out system EMC control plan. If formulated well ahead of the design of the system, duplication of filtering on interconnecting leads will be avoided. One precaution should be observed, however, when considering the reduction of redundant filters; equipment at both ends of the cable must be able to tolerate the noise levels passed in both directions.

FILTER TYPES AND APPLICATION

Filters are electrical circuit configurations designed to attenuate at certain frequencies while permitting currents at the desired frequencies to pass. They do this by using combinations of capacitances and inductances to set up a high impedance in series with, or a low impedance shunt to ground for, the interfering currents. The passband of a filter is the frequency region in which there is little or no attenuation. The transmission characteristics are not necessarily uniform but the variations are usually small. The stopband is the frequency region in which attenuation is desired. The attenuation may vary in the stopband and is usually least near the cutoff frequency, rising to high values of attenuation at frequencies considerably removed from the cutoff frequency. Filters can be classified according to the position of the passband in relation to the stopband on the frequency spectrum. There are four classes: low-pass, high-pass, bandpass, and band-reject. Attenuation as a function of frequency for each of these classes is shown in Figure 14-1.

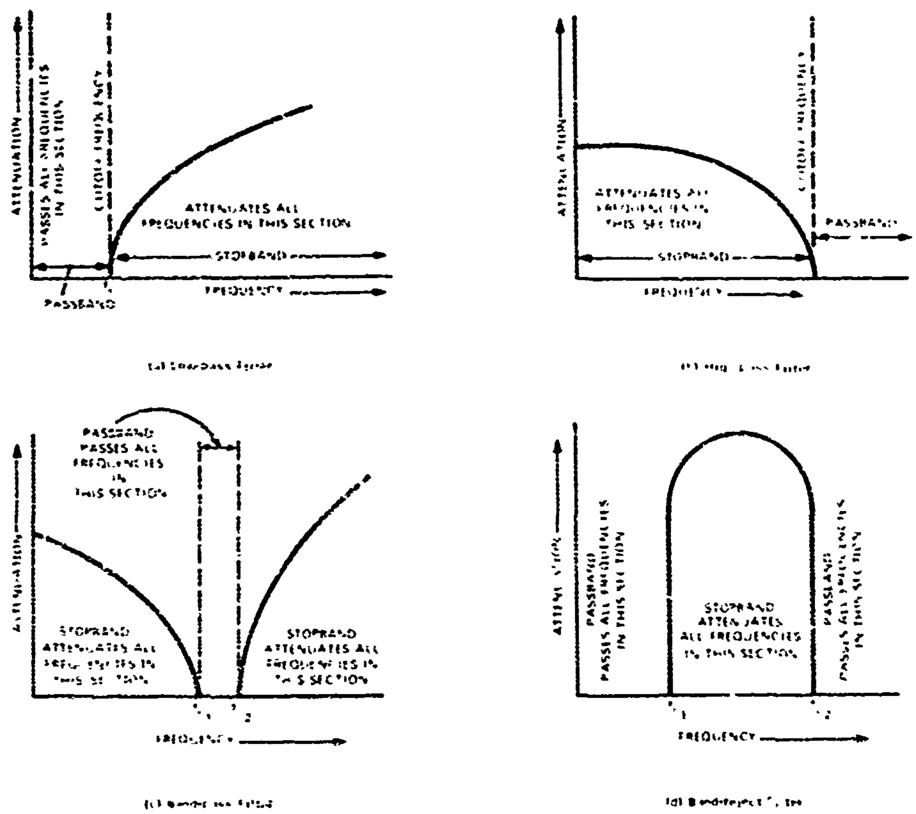


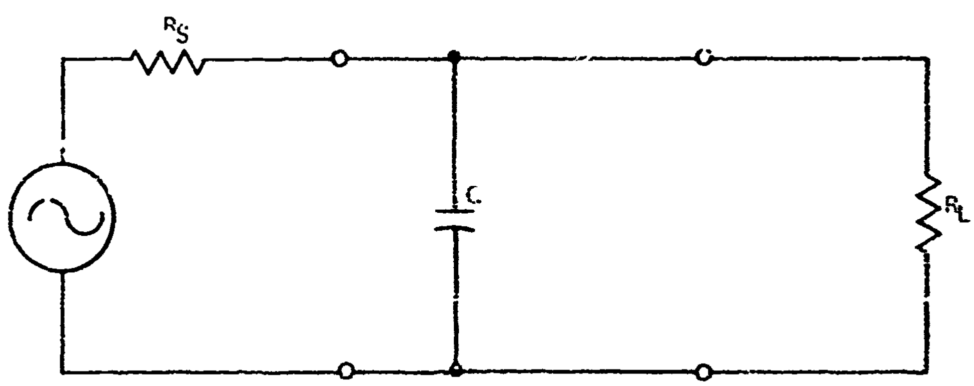
FIGURE 14-1 FOUR CLASSES OF FILTERS

The control of EMI usually requires filters of the low-pass type. Power line filters are of the low-pass type to pass DC or power frequency currents without significant power loss while attenuating all signals above the cutoff frequency. Filters incorporated in amplifier circuits and output circuits are usually of the low-pass type so that the fundamental signal frequency can be passed while harmonics and other spurious signals are attenuated. The following discussion describes the various types of low-pass filters used in the control of EMI.

These filters are generally made of discreet elements of capacitance and inductance and are often referred to as lumped-constant devices to distinguish them from distributed constant devices such as transmission lines, coaxial cables, or dissipative filters using ferrites.

Shunt Capacitive Filters

There are many forms of filters for interference reduction, with the configuration depending on the frequencies to be filtered out. The simplest interference reduction filter is a shunt capacitor connected from the interference-carrying conductor to ground. A capacitor exhibits capacitive reactance until the self-resonant frequency is reached. Above this frequency the capacitor behaves like an inductive reactance.



$$IL \text{ (in dB)} = 10 \text{ LOG } [1 + (\pi f C R)^2]$$

FIGURE 14-2 DETERMINATION OF INSERTION LOSS

Refer to Figure 14-2. The theoretical insertion loss of a shunt or parallel-connected capacitor in a line, where source and load impedances are equal, is:

$$IL = 10 \log \left[1 + (\pi fCR)^2 \right] \quad (14\text{-}1)$$

wherein:

- IL = Insertion loss in dB
- f = Frequency in MHz
- C = Capacity in microfarads
- $R_S = R_L$ = Source or load impedance in ohms

When $fCR >> 1$ (in practical terms, above the cutoff frequency):

$$IL = 20 \log (\pi fCR) \quad (14\text{-}2)$$

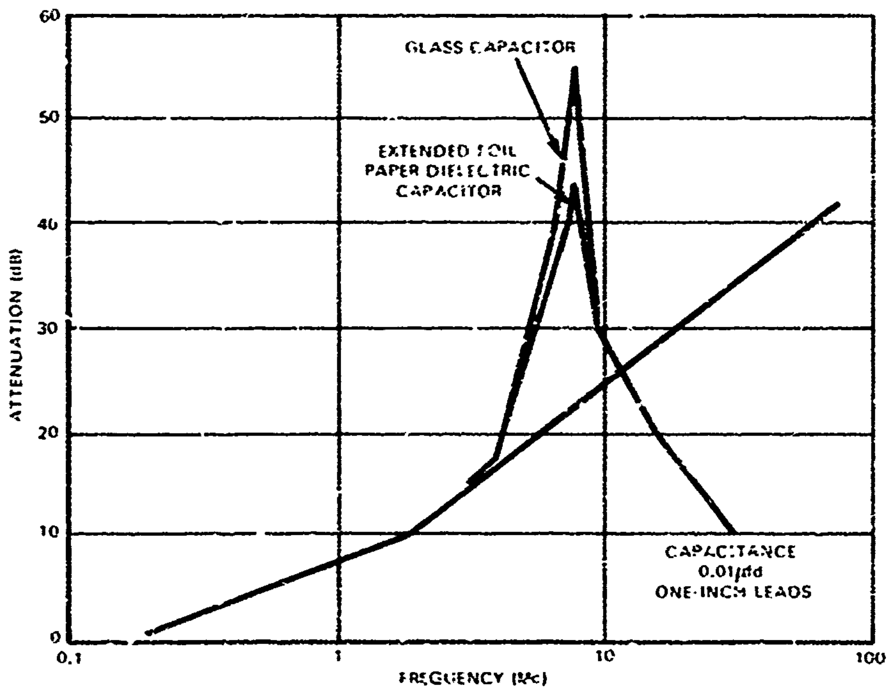


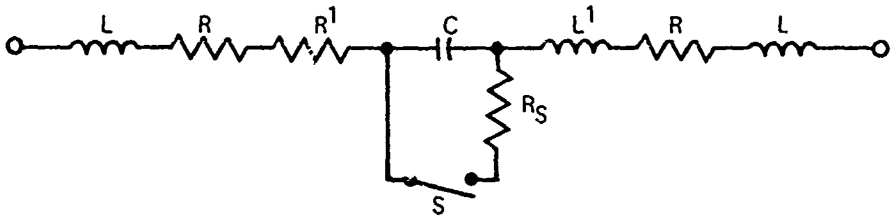
FIGURE 14-3 TYPICAL BYPASS CAPACITOR FREQUENCY CHARACTERISTICS

However, a capacitor is not ideal: because of self-inductance, lead inductance, foil resistance, and lead-to-foil contact resistance, the characteristics of a practical capacitor do not coincide with the theoretical value. Figure 14-3 illustrates the characteristics of several types of capacitors. The variation from ideal capacitor characteristics depends upon the type of capacitor. Metalized paper capacitors, while small in physical size, offer poor RF bypass capabilities because of high resistance contact between the leads and the capacitor metal film. They are also a source of radio noise as the dielectric punctures and self-heals by burning away the metal film. This effect is indicated by the switch

in the equivalent circuit shown in Figure 14-4. The standard-wound aluminum foil capacitor is useful as a radio frequency bypass in the frequency range up to 20 MHz. Its useful frequency range of operation is a function of capacitance and lead length. The equivalent circuit is shown in Figure 14-5.

Mica and ceramic capacitors of small values are useful up to 200 MHz. A capacitor of flat construction, particularly if the capacitor plates are round as in a ceramic disc capacitor, will remain effective to higher frequencies than one of square or rectangular construction.

A number of other factors must be considered in the selection of ceramic capacitors as filter elements. A ceramic capacitor element is affected by operating voltage, current, frequency, age, and ambient temperature. The amount the capacity varies from its nominal value is determined by the composition of the ceramic dielectric material. This composition can be adjusted to obtain desirable characteristics such as negative temperature or zero temperature coefficient or minimum size. In obtaining one desirable characteristic, the other characteristics may become undesirable for certain situations. For example, while the dielectric composition is adjusted to produce minimum size capacitors, the voltage characteristic may become negative to the extent that 50 percent capacity exists at full operating voltage and full ambient temperature may cause an additional sizeable reduction in capacity.



L Lead Inductance

R Lead-to-Foil Contact Resistance

R^1 Resistance of Metallized Foil

C Capacitance

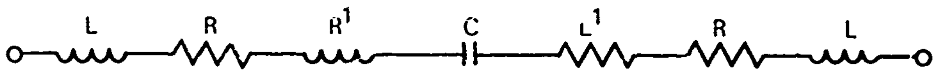
L^1 Foil Inductance

S Short Circuit due to Voltage Puncture

R_S Short Circuit Resistance

FIGURE 14-4 METALIZED CAPACITOR EQUIVALENT CIRCUIT

The designer should make his capacitor selection on the basis of true capacity under the most adverse of operating conditions, also taking into account the aging effect. From the time of firing of the ceramic, the dielectric constant of the materials used may decrease. After 1000 hours, the capacitance may be as low as 75 percent of the original value.



L Lead Inductance

R - Lead-to-Foil Contact Resistance

R^1 Foil Resistance

C Capacitance

L^1 - Foil Inductance

FIGURE 14-5 WOUND ALUMINUM FOIL CAPACITOR EQUIVALENT CIRCUIT

Three-Terminal Capacitive Filters

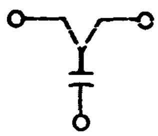
Capacitors of short-lead construction and feed-through capacitors are three-terminal capacitors designed to reduce inherent and lead inductances. Figure 14-6 shows the construction of the three-terminal types. In each case, the inductance of the lead is not included in the shunt circuit. The wound foil capacitor is made with an extended foil type construction so that each plate of the capacitor can be soldered to a washer shaped terminal. One washer is, in turn, soldered to the center lead, while the other is soldered to the case that is the ground terminal.

Theoretical insertion loss of three-terminal capacitors is the same as for an ideal two-terminal capacitor.

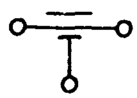
When $fCR >> 1$ (in practical terms, above the cutoff frequency):

$$IL = 20 \log (\pi f C R) \qquad (14\text{-}3)$$

wherein: IL = Insertion loss in dB
f = Frequency in MHz
C = Capacity in microfarads
R = Line impedance in ohms

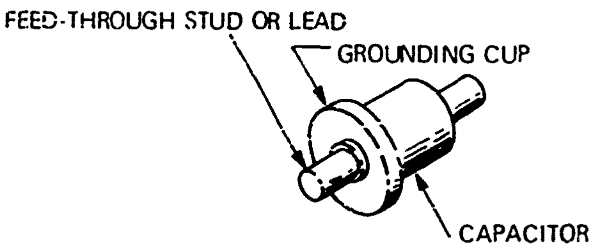


a. ELECTRICAL CIRCUIT OF A
SHORT-LEAD CAPACITOR.

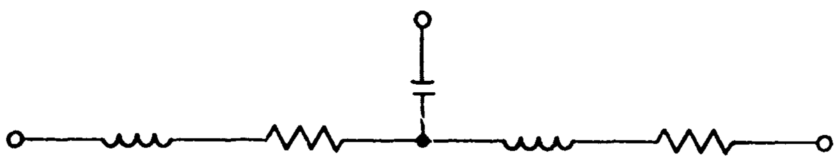


b. ELECTRICAL CIRCUIT OF A
FEED-THROUGH CAPACITOR.

c. CONSTRUCTION OF A SHORT-LEAD CAPACITOR. THE USE OF FLAT LEADS WILL INCREASE CONTACT AREA AND REDUCE LEAD INDUCTANCE.



d. WOUND FOIL FEED-THROUGH CAPACITORS
ARE OF EXTENDED-LEAD CONSTRUCTION.



e. ELECTRICAL EQUIVALENT OF A SHORT-LEAD OR
FEED-THROUGH CAPACITOR

FIGURE 14-6 THREE-TERMINAL CAPACITOR CONSTRUCTION

However, the insertion loss of a real three-terminal capacitor follows the theoretical curve much more closely than does a two-terminal capacitor. The useful frequency range of a feed-through capacitor is improved further by its case construction in which a bulkhead or a shield usually isolates the input and output terminals from each other.

While the three-terminal capacitor is ideally suited to EMI suppression in the frequency range of 1 to 1000 MHz, feed-through capacitors are now

available with a resonant frequency well above 1 GHz. The feed-through current rating is determined by the stud diameter. Figure 14-7 shows the attenuation of a typical three-terminal capacitor.

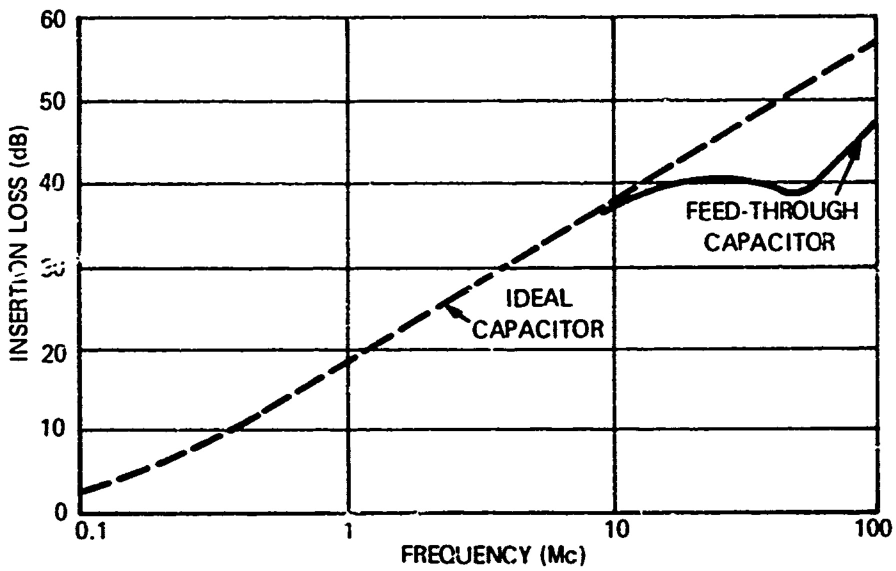


FIGURE 14-7 INSERTION LOSS OF TYPICAL THREE-TERMINAL CAPACITORS

"L" Section Filters

Attenuation in the low frequency range can be increased by the addition of an inductor in series with the circuit carrying the signal. This addition forms a circuit known as an "L" section lumped-constant filter.

The theoretical insertion loss of an "L" section lumped-constant network is:

$$IL = 20 \log \left(1 + \frac{\omega CR}{2} + \frac{\omega L}{2R} + \frac{\omega^2 LC}{2}\right) \qquad (14\text{-}4)$$

wherein:

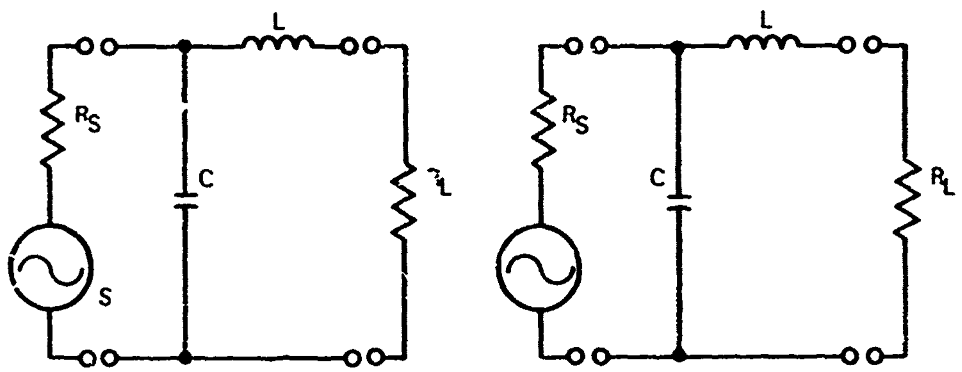
IL	=	Insertion loss in dB
ω	=	$2\pi f$
f	=	Frequency in MHz
C	=	Capacitance in microfarads
L	=	Inductance in microhenries
R	=	Line impedance (resistive) in ohms

Above cutoff, where $\omega L >> R >> 1/\omega C$

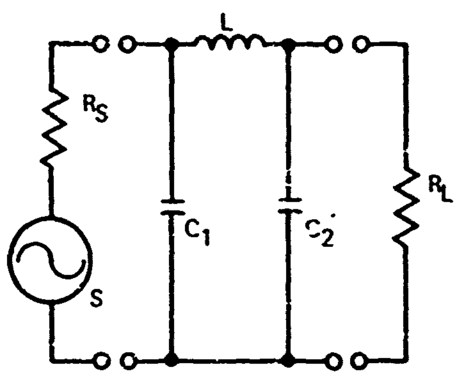
$$IL \approx 20 \log \frac{\omega^2 LC}{2} = 20 \log 2\pi^2 f^2 LC \qquad (14\text{-}5)$$

Notice that as frequency is increased by a factor of ten above the cutoff frequency, insertion loss increases by 40 dB.

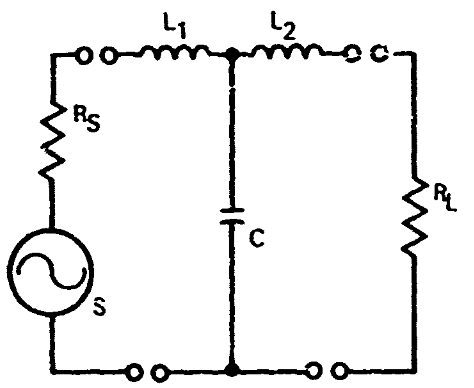
The theoretical insertion loss for the "L" section filter is independent of the direction of inserting the "L" section in the line, if source and load impedances are equal. Figure 14-8 (a) shows the two configurations for an "L" section filter. On the left, the capacitor shunts the source impedance, while on the right the capacitor shunts the load impedance. When source and load impedance are not equal, the greatest insertion loss will usually be achieved when the capacitor shunts the higher impedance.



a. L-SECTION FILTERS



b. Pi-SECTION FILTER



c. T-SECTION FILTER

FIGURE 14-8 LUMPED-CONSTANT LOW-PASS FILTERS

The physical size of an "L" section filter depends upon insertion loss requirement, current rating, and voltage rating, with the first two usually predominant. The "L" section type of filter may give poor high frequency attenuation because of stray inter-turn capacitance. In some cases, the "L" type may resonate and oscillate when excited by transients.

"pi" Section Filters

The "pi" section filter is the most common type of radio frequency interference suppression network. Figure 14-8(b) shows the circuit of the "pi" section filter. Advantages are ease of manufacture, high insertion loss over a wide frequency range, and moderate space requirements. Although voltage rating must be considered, current rating and attenuation are the most important factors in determining the size of the filter.

The insertion loss of an ideal "pi" section network is:

$$IL = 20 \log \left(1 + \omega CR + \frac{\omega L}{2R} - \omega^2 LC - \frac{\omega^3 LC^2 R}{2}\right) \quad (14\text{-}6)$$

wherein:

IL	=	Insertion loss in dB
ω	=	$2\pi f$
f	=	Frequency in MHz
C	=	Total capacity in microfarads
L	=	Inductance in microhenries
R	=	Line impedance (resistive) in ohms

Above cutoff or when $\omega L > R$ and $\omega C > R$:

$$IL \approx 20 \log \frac{\omega^3 LC^2 R}{2} = 20 \log 4\pi^3 f^3 LC^2 R \quad (14\text{-}7)$$

A typical attenuation curve of a "pi" section filter has a slope of approximately 18 dB per octave, and the high frequency performance can be improved by internal shielding within the filter case. The "pi" circuit is, however, very susceptible to oscillatory ringing when excited by a transient.

A multiple "L" section filter is composed of individual "L" sections arranged in series combining the best characteristics of individual "L" sections and "pi" section filters–and adding an important one of its own: fast rise of attenuation versus frequency above cutoff.

The theoretical slope of an LC network filter rises at a rate of 40 dB per "L" section for each decade increase in frequency. This means that a triple "L" section will rise 120 dB per decade of frequency compared to 60 dB for a "pi" section and 20 dB for a capacitor under the same conditions. A double "L" section filter is seldom used in practice; a "pi" section network is the most common network.

The multiple "pi" section filter has characteristics identical to those of the

multiple "L" section filter. The attenuation curve of the theoretical multiple "pi" section filter rises at a rate of 20 dB more per decade of frequency than does a multiple "L" filter of the same number of sections. Although this is not a large increase in attenuation when three or more sections are used, it does provide a capacitive input at both ends of the filter that is sometimes advantageous.

The greatest use for this type of network is in large installations, and for shielded rooms where high attenuation is needed at very low frequencies. The rapid attenuation rise of a multiple "pi" section can be used to achieve a cutoff higher than the power frequency, yet still permit high attenuation in the low frequency spectrum. This technique is rarely applied to airborne equipment and vehicles because of the size of this type of filter. A specially designed M-derived section to achieve the low frequency attenuation in series with a standard "pi" section or "L" section filter has been the standard practice when low frequency attenuation is required. Though the M-derived filter is much higher in cost, it is much smaller and lighter than a multiple-section "pi" filter.

"T" Section Filters

The lumped-constant type of filter can be further sophisticated by the introduction of another inductor to an "L" section filter. This addition forms a "T" section lumped-constant filter, which consists of two inductors in series with the signal-carrying wire with a shunt capacitor connected from the junction of the two inductors to ground.

The "T" type of filter is a very effective form of the lumped-constant type of filter for reducing switching transient interference, although the requirement for two inductors places quite a penalty on it Reduction of transients has become a very important part of EMI control. Military standards and specifications now include requirements for transient as well as steady state tests. Present-day electronic equipments use a digital format extensively, and such equipment is incapable of distinguishing an EMI transient from a normal digital signal of similar envelope or rise time. Typical "L," "pi," and "T" section filters are shown in Figure 14-8. Lumped-constant low-pass filters, except the single element R-C filter, use series inductors, and the standard method of insertion loss measurement in accordance with MIL-STD-220A. Operation of lumped-constant filters at or near saturation will differ from operation at rated current. The series inductors are generally wound on toroidal cores of ferromagnetic material (to limit external fields) with a relative permeability of about 125. The size of the core and the ampere-turns will determine the saturation characteristics of the core and the resultant loss in permeability. The use of ferrous cores is dictated by the need to achieve maximum inductance at minimum I^2R wire losses. The degradation of attenuation is a function of current, mismatch between the line and load impedance, the steady-state reactance of the source and load, and the variation of the load in terms of time.

The usual "pi" or "T" filters intended for broadband interference filtering are generally composed of relatively low loss inductive capacitive

lumped-constant elements. Such filters cannot dissipate much energy within their rejection range; they merely reflect it so that under certain conditions it may reappear elsewhere as an undesirable signal or interference. Where source and load impedance are mismatched, the insertion of a filter may improve the source to load impedance match. Since the filter can serve to match source and load impedances, insertion of a filter may actually increase the EMI voltage (or current) appearing in the load. In other words, the filter in that circuit at certain frequencies could behave as though it had a negative insertion loss.

Dissipative Filters

Unlike carefully designed laboratory circuits used for insertion loss measurements, where source and load impedances are fixed at exactly 50 ohms resistance, the impedance that a filter sees in most practical powerline applications is extremely variable with frequency, ranging from very high to very low impedance, with wide variations of phase angle. Examples of this effect have been observed in which the insertion of a reactive filter into a line carrying interference has actually resulted in more, rather than less, interference voltage appearing on the line beyond the point of application. This deficiency, inherent in all filters composed of low loss elements, has led to the investigation of dissipative types of filters that take advantage of the loss-versus-frequency characteristics of magnetic materials such as ferrites.

One form of dissipative filter uses a short length of ferrite tube with conducting silver coatings deposited in intimate contact on the inner and outer surfaces to form the conductors of a coaxial transmission line. The line becomes extremely lossy; that is, it has high attenuation per unit length in the frequency range where either electric or magnetic losses, or both, become large and increase rapidly with frequency. Dissipative filters of this type are necessarily low-pass. One of the large uses of such filters is in general-purpose powerline filtering, in which the dissipative filter is combined with conventional low loss elements to obtain the necessary low cutoff frequency.

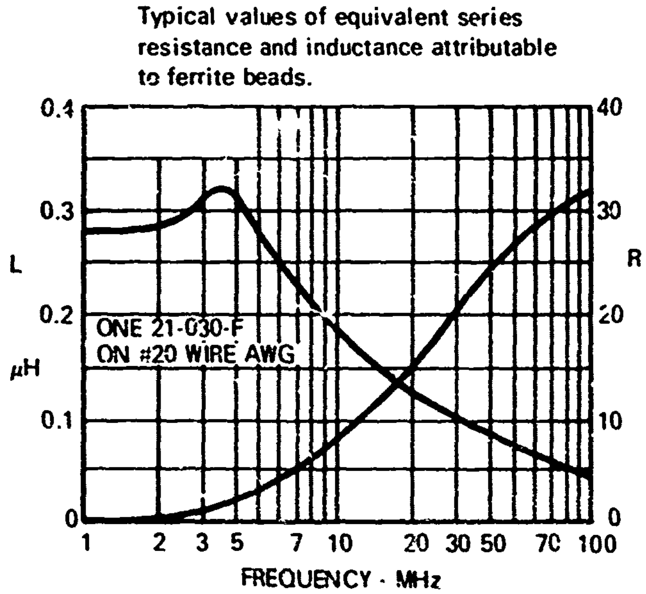
Ferrite Bead Filters

Ferrite beads provide a simple, economical method for attenuating unwanted high frequency noise or oscillations. One bead slipped over a wire produces a single turn RF choke that possesses low impedance at low frequencies and moderately high impedance over a wide high frequency band. The efficacy of this impedance in reducing noise will depend upon the relative magnitude of the source, suppression, and load impedances.

The presence of a ferrite bead on the wire causes a local increase of series inductance and resistance presented to currents in the wire. Figure 14-9 illustrates the effects of one ferrite bead on a length of wire. Adding more or longer beads provides additional units of series inductance and resistance in direct proportion. This technique is effective at all frequencies. Extra turns of wire can be passed through the bead, increasing both resistance and inductance

in proportion to the square of the number of turns. Because of distributed winding capacitance, this technique is most effective at the lower frequencies. There will also be an increase in DC resistance.

High amplitude DC or low frequency signals will cause some reduction in the suppression effect. However, as long as only one turn links the core, fairly high currents can be tolerated before saturation is approached. At saturation, inductance and resistance will be low, but will return to normal values upon removal of the high field. High RF levels can cause excitation greater than that used for the measurements shown in Figure 14-9. Generally, these will cause the effective resistance to increase because of the contribution of hysteresis losses.



TYPICAL PROPERTIES	
Flux Density (B) at 5 O_e	2400 G
Coercive Force (Hc)	0.56 O_e
Hysteresis Factor ($h \cdot \mu^2$)	22×10^{-6}
Initial Permeability (μo)	450
Permeability (μ) at 250G	900
Resistivity - Ohm - cm	$\geq 10^7$
Curie Temperature	$\geq 155\,^{\circ}C$

FIGURE 14-9 FILTER CHARACTERISTICS OF FERRITE BEADS

Ferrites are inert ceramics free of any organic substances. They will not be degraded by most environments. Properties will vary somewhat with temperature. Generally, inductance increases with increasing temperature, while the effect on resistance is small. Above the Curie temperature, the bead is nonmagnetic and no suppression can be expected. The effect is, however, completely reversible, and once the temperature is reduced below that point, normal performance is regained.

Because of the high resistivity of ferrite beads, they may be considered insulators for most applications.

FILTER SELECTION AND USE

In designing or selecting a filter for a particular application, many parameters must be taken into account if the filter is to be most effective.

Attenuation, insertion loss, and frequency range of attenuation are the primary electrical characteristics that determine the suitability of a filter for a particular EMI application. Size, weight, cost, and reliability are also important design considerations, particularly in aerospace systems.

If a filter does not provide the minimum attenuation required for the stopband, then the filter is not satisfactory no matter how suitable the other characteristics may be. The attenuation is defined as the ratio of the filter input voltage to the filter output voltage under normal circuit conditions:

$$\text{Attenuation (dB)} = 20 \log \frac{E_i}{E_o} \qquad (14\text{-}8)$$

Wherein,

E_i = Voltage across filter input terminals
E_o = Voltage across filter output terminals

The attenuation in dB from this formula does not consider the source and load impedances, and therefore does not give a true indication of the suppression effectiveness of the filter. Insertion loss measurement presents a far more reliable picture, since it is a function of the source impedance, load impedance, and the filter itself. Insertion loss is defined as the ratio of the voltages, at a given frequency, across the load terminals before and after the filter is inserted into the circuit:

$$\text{Insertion loss (dB)} = 20 \log \frac{E_1}{E_2} \qquad (14\text{-}9)$$

wherein:

E_1 = load voltage without the filter in the circuit
E_2 = load voltage with the filter in the circuit

Design Tolerances

Insertion loss figures quoted by a filter manufacturer are usually normalized for a 50-ohm system. If the circuit to be filtered does not have both 50-ohm input and output impedances, the insertion loss will differ from the quoted value. The difference may amount to 20 dB or more.

A determination of filter insertion loss requirements must take into account that different samples of the same device to be filtered will differ somewhat in interference emission or susceptibility characteristics. Tolerances on filter element values will also cause filters to vary slightly in performance. For these reasons, it is important to allow a safety margin in calculating insertion loss requirements. It is a common practice to allow at least a 6-dB margin in the stop band.

Other characteristics that must be considered in filter selection are:

1. Voltage rating of the circuit in which the filter is to be used
2. Maximum current that will pass through the filter
3. Operating frequencies of the filter and the frequencies to be filtered
4. Maximum voltage drop across the filter at its operating power frequencies
5. Maximum and minimum temperatures at which the filter will be operating
6. Minimum filter life (number of hours that a filter will be required to operate under rated conditions at the minimum ambient temperature)
7. Size, weight, and cost restrictions on the filter

Inductor Design

Filter inductors are usually toroidal, wound on cores of powdered iron, molybdenum permalloy, or ferrite material. The size of the core is determined by required inductance and current rating. The magnetic flux (number of turns multiplied by the peak current) must not drive the core to more than 50 percent of magnetic saturation. The choice of core materials is determined by operating frequency and current rating. Powdered iron cores can be used for all DC applications and for most 60 Hz applications. For high current 60 Hz devices, and for all 400 Hz applications, molybdenum permalloy cores must be used. For extremely low current applications of less than 0.1 ampere, ferrite materials can be considered.

Windings should be placed on the coil so that input and output turns are separated as much as possible. Each turn of the coil will be at a slightly different instantaneous potential, therefore there is capacitance from each turn to adjacent turns, depending on the spacing and area of each successive turn. There is also capacitance between the coil terminals. Stray or distributed capacitance in a filter inductor can have two detrimental effects from the EMI suppression viewpoint: EMI may be coupled from input to output of the filter via the

capacitance, when input and output turns (or terminals) are close together, and the capacitance may cause the filter to become self resonant at one or more critical frequencies. Distributed capacitance effects are reduced by a careful arrangement of turns to minimize the potential difference between them. In some cases, two or more coils wound on separate cores are connected in series to raise the self resonant frequency. Thus, a given inductance split into two equal parts, and without mutual coupling, will have a resonant frequency twice as high as a single coil of the same total inductance.

Loss resistance R_L is a measure of all power losses, hysteresis losses, and frequency dependent absorption losses in the core. Loss resistance R_L increases with frequency because of skin effect in the conductor and because of changes in core losses with frequency. The losses represented by R_L enter directly into the impedance equations for filter design as do the capacitive reactances and flux linkages. Each has an influence on the magnitude and phase angle of the impedances. An increase in R_L represents an increase in the attenuation of the filter passband. Its effect on reflection losses will depend upon its relation to the source and load impedances. Losses in the core are not particularly detrimental except when the insertion loss in the passband must be kept low.

The losses in the windings, plus losses in the core, cause heating of the filter. This heating must be taken into consideration when rating the filter for ambient temperature conditions. An empirical relationship has been developed that indicates approximate temperature rise of the filter case:

$$\text{Temperature rise } (^\circ\text{C}) = \frac{\text{Watts}}{0.006A} \qquad (14\text{-}10)$$

Wherein:

A = total surface area in square inches.

This expression is based on the heat dissipation of tinned steel cans.

Capacitor Design

Capacitor selection is determined in part by the voltage, temperature, and frequency range in which the filter must operate. Most EMI powerline filters are rated for certain standard voltages.

For 28 VDC applications, capacitors rated at 100 WVDC are quite adequate Metallized mylar capacitors offer the most compact design and good reliability. The dissipation factor is very low and lead length can be kept short to improve high frequency performance.

If a large value of capacitance is required in a small space, tantalum capacitors may be considered. Because tantalum capacitors are electrolytics,

they are more sensitive to over-voltages, and are damaged by reverse polarity. The dissipation factor is considerably higher than for mylar or paper capacitors, and high frequency characteristics are poor. A fairly large tantalum capacitor reaches its minimum impedance at 2 to 5 MHz or less, depending upon construction and capacitance value.

Capacitors for 120 VAC applications should be rated at 400 WVDC and be suitable for AC use. A unit of mylar and foil or of paper-mylar and foil is recommended. Dissipation factor is low and high frequency performance is good. For 240 VAC applications, an oil impregnated paper and foil unit is recommended.

If good capacitor performance is to be expected above about 50 MHz, it is necessary to use design incorporating feedthrough capacitors. Lead inductance in a feedthrough capacitor is not part of the shunt circuit, so that, compared to capacitors with leads, its insertion loss is not degraded as rapidly with increase in frequency (see Figure 14-7).

FILTER INSTALLATION

Once a filter has been selected, its contribution to EMI control must not be degraded through faulty installation. For control of high frequency EMI, filter installation requirements become very critical.

A filter should be located as close as possible to the source of EMI for suppression, and as close as possible to the susceptible circuit for protection against external interference sources. Ideally, a filter should be mounted at a point where the conductors being filtered pass through a natural boundary such as a chassis or shielded enclosure. This style of mounting tends to prevent interference from coupling across the filter input to output.

For good high frequency performance, input and output wiring should be effectively separated. Otherwise, EMI emitted from the input leads can couple directly into the output wiring and thus nullify the effects of the filter. Separation of wiring is most easily achieved by mounting the filter through the chassis so that the output leads protrude through the chassis or bulkhead and are shielded by it. When this is not possible, the wiring should be isolated by shielding. The leads on the "clean" side of the filter should not be routed through a region containing interference fields. If this is unavoidable, then the leads should be shielded carefully to prevent recontaminating them. In no case should the filter input and output leads be bundled together. Only when the output of a filter is completely isolated from the input can the filter insertion loss achieve the design figure.

An important factor in filter performance is the bonding of the filter case to the ground plane structure of the suppressed or protected device. This requirement is of the utmost importance if the filter is to achieve its design capability. The mounting surface for the filter must be a clean conductive area.

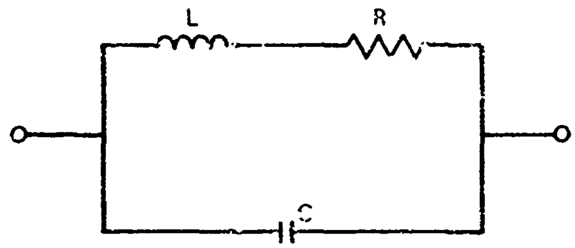


FIGURE 14-10 SIMPLE WAVETRAP CIRCUIT

SPECIAL EMI SUPPRESSION NETWORKS

A number of special networks and circuits have been developed to reduce radio interference. Four of the more important ones are treated in this subsection.

WAVETRAPS AND NOTCH FILTERS

Wavetraps and notch filters are circuit networks designed to attenuate a specific narrow band of frequencies that may be causing interference problems. This type of device is normally used as a band-reject filter between the interference source and the load. An alternative is to use a bandpass configuration that shunts the interference to ground.

A wavetrap may take the form of a lumped-constant inductor-capacitor circuit, or it may be a shorted quarter-wave coaxial or waveguide stub, or a crystal or ceramic filter lattice. The inductive characteristics of capacitor leads and foil can be planned so that the capacitor acts as a self-contained wavetrap. For frequencies below about 1 MHz, a twin-T resistor-capacitor filter can serve.

The simplest type of wavetrap is a parallel resonant circuit such as that shown in Figure 14-10. This configuration will give a very high impedance at the anti-resonant frequency, and therefore this frequency is attenuated greatly. The impedance of this circuit is given by:

The twin-T notch filter, shown in Figure 14-12, is useful as a band-reject filter in the lower frequency ranges such as the IF and AF circuits. At low frequencies, the twin-T filter can achieve a circuit Q on the order of 100, which would not be economically feasible for a wavetrap or inductance capacitance type filter at the same frequency. Because the twin-T is a three-terminal filter, shunting effects reduce its usefulness at high frequencies. The notch frequency is determined by:

$$f_o = \frac{1}{4\pi C_1 R_1} \tag{14-12}$$

Where:

f_o = Tuned frequency
C_1 = Capacitance identified in Figure 14-12
R_1 = Resistance identified in Figure 14-12

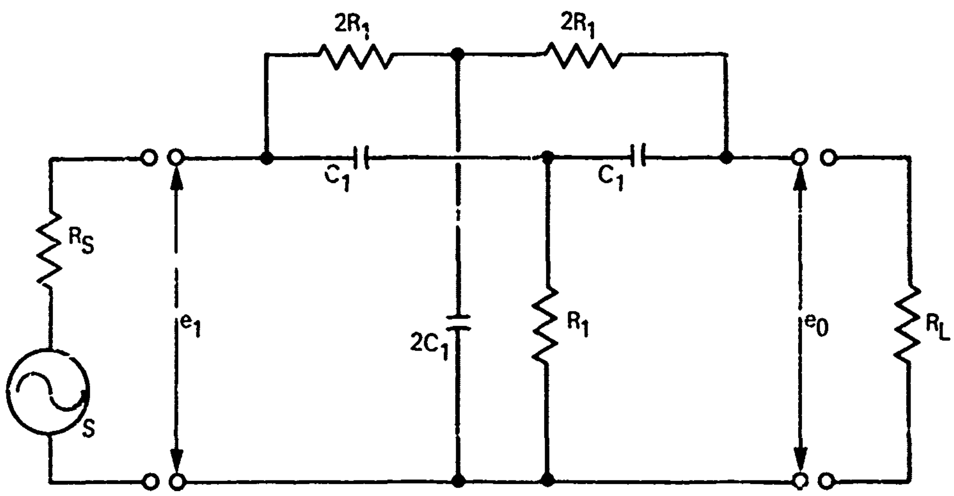


FIGURE 14-12 TWIN-T NOTCH FILTER

Typical applications and locations of wavetrap, crystal, ceramic, and twin-T notch filters include the following:

1. At receiver input terminals to reject strong nearby out-of-band interference that otherwise would overload the receiver
2. At receiver input terminals to reject troublesome image frequencies
3. At receiver input terminals to reject IF-feedthrough signals
4. At transmitter output or interstage terminals to reject harmonics or unwanted mixer products
5. In AC or DC power distribution leads to reject EMI such as radar PRF, computer-clocked surges, or rectifier ripples
6. At audio amplifier input or interstage terminals to reject IF or BFO feedthrough, unwanted heterodynes, signal tones, radar PRF

NOISE LIMITERS

For interfering signals consisting of short impulses of large amplitude, noise limiters can prevent the peak amplitude of the interference from rising above the wanted signal. Noise limiters are not effective against thermal noise or any other type of steady-state EMI except in FM receivers or Dicke-fix receiver applications. There are two types of noise limiters in current use: the peak amplitude limiter and the gated noise limiter.

The peak amplitude limiter reduces the effect of interference by clipping all impulses above a certain threshold region. To be most effective, the clipping level should be as close as possible to the peak level of the desired signal, but not set to clip so heavily as to produce significant degradation of the desired amplitude modulation. FM receivers can clip heavily because the desired information is contained in the frequency components rather than the amplitude components of the signal.

Dicke-fix receivers also clip heavily in the early stages of receivers that use sufficient bandwidth so as not to distort the noise power spectrum appreciably. Noise power occupies much more spectrum than the desired signal, and heavy amplitude clipping in wideband stages can prevent noise power amplitude from exceeding signal power amplitude. The amplitude of the wanted signal power can then be enhanced above noise by processing the signal-plus-noise through narrowband stages that use bandwidth limiting but not amplitude limiting. The degree of enhancement is a function of the ratio of the two bandwidths. Several successive stages of a receiver may employ amplitude limiting to provide progressive degrees of limiter action. Diode devices are commonly used, although tube or transistor amplifiers biased to swing into a nonlinear region on strong signals may also be used. The 6BN6 and similar tubes are especially designed for this purpose. The disadvantage of peak amplitude limiters is that they introduce nonlinearity and the resultant possibility of cross-modulation on strong signals.

The gated noise limiter is an audio frequency device usually located between the detector and the first audio amplifier. Basically the circuit consists of a diode or combination of diodes having a fast time constant network at the input, and a slower time constant network at the output. As long as the charge-discharge period at the output can follow the desired audio input signal from the detector, the diode gate continues to conduct and the input signal is delivered to the audio amplifier. However, an impulse from the detector will possess a rise-decay rate greater than that provided for at the noise gate output. This will cause the gate to be back-biased and cut off momentarily until the slower time constant at the output can catch up with the input. Noise impulse steep wavefronts are thus kept from coming through, except for that portion attributed to capacitive coupling. The gated noise limiter is beneficial only when used with near-sinusoid waveforms such as speech.

The usefulness of both types of noise limiters depends on the width of the receiver bandpass. It must be broad enough to avoid receiver "ringing" on noise impulses. Bandwidth-limiting can alter the noise impulse envelope so that subsequent limiter action is ineffective.

BLANKING CIRCUITS

If the interfering signal is a pulse and there is no other way of protecting the receiver, a blanking circuit can be used. A blanking circuit protects the receiver by rendering it inoperative for the duration of the pulse.

The blanking circuit can be triggered by the interfering pulse or by an independent signal arriving before the interference pulse. When the interference pulse triggers the blanking circuit, delay lines must be provided to delay the signal long enough to allow the blanking circuit to turn off the receiver before the interference pulse reaches it. An independent pulse can be used if the arrival of the interference pulse is known beforehand, as when it comes from other equipment in the same aircraft. In this case, the triggering pulse can be provided by the interfering piece of equipment. Blanking action is usually provided by a simple circuit that can be gated off by the trigger pulse.

Blanking circuits lack the simplicity of wavetraps and limiters. They are complete units in themselves and include amplifiers, trigger pulse amplifiers, and delay circuits. They can also cause interference in themselves. The periodic cutting off of the signal is a form of modulation, which will appear in the audio output as noise.

INTERFERENCE CANCELLING CIRCUITS

An interference cancelling circuit suppresses interference by allowing the interference signal to travel along two paths. One of the two paths carries the interference signal and the desired signal; the other carries only the interference signal. The interference signal is then shifted 180 degrees in phase, adjusted in amplitude, and added to the other signal, thus cancelling the interference and leaving the desired signal. This method can be used only when the path of entry

and the nature of the interfering signal are known. Interference cancelling circuits are useful in suppressing interference from equipment in the same aircraft that give out definite interference signals, such as radar transmitters.

Figure 14-13 illustrates one arrangement for eliminating interference by cancellation. Two directional couplers are used. One, indicated as DC-1, samples the interfering signal at the offending transmitter. The signal is routed through delay lines to introduce the required phase shift, through attenuators to set the power level, and then coupled to the receiver via another directional coupler, indicated as DC-2.

The arrangement shown in Figure 14-13 can be used only when the interfering transmitter is in the same vehicle as the affected receiver. The directional couplers are of the type commonly used for SWR measuring devices and other test purposes. They introduce negligible insertion loss in the main through-line path.

For cancelling interference sources not in the same vehicle, a different pickup arrangement will be needed, and the phase and attenuation control methods will be more complex.

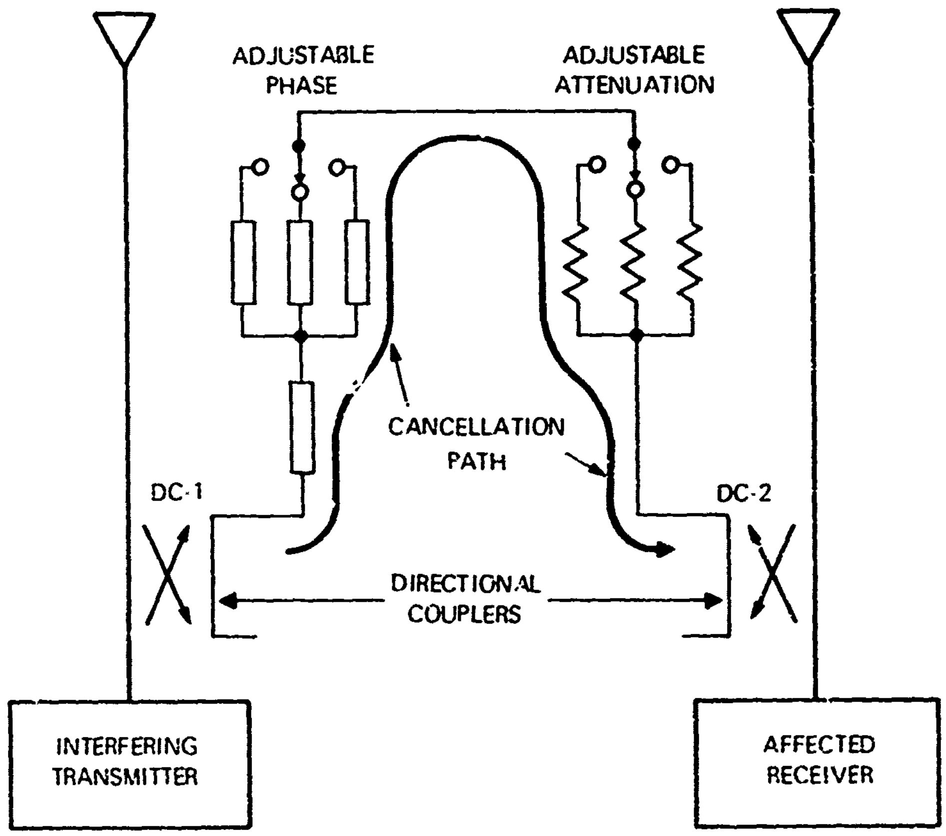


FIGURE 14-13 BLOCK DIAGRAM OF AN INTERFERENCE-CANCELLING NETWORK

ACTIVE FILTERS

EMI power line filters made of passive elements are bulky and heavy. Active filters, using transistors, can provide large values of L and C without excessive size and weight. Moreover, the low impedance levels existing at low frequencies in power lines can be more easily accommodated. Two major criteria exist in analyzing the filtering conditions:

1. Power flow (DC, 60 Hz, 400 Hz) with respect to the interference flow
2. Either voltage or current attenuation as the dominant and desired feature

For the power flow criterion, three basic conditions must be distinguished. The first is the interference originating in the power supply and flowing toward the load, as in filtering a power line supplying a shielded room. The second involves interference originating in the load and flowing toward the power supply. An example is the spreading of interference arising from SCR switching, computers, and other digital equipment or solid state choppers, through the power distribution system. Another example is current pulses that drive a teletypewriter and carry classified information must be confined within a secure area. The third condition covers those cases in which interference is generated both at the power source and load, or where there is uncertainty about its origin. In these cases, bidirectional filters are required.

Underlying Principles of Operation

There are four well-known methods that can be used alone or judiciously combined to prevent interference from passing through a network. They are:

1. Storing and averaging out the interference (such as through the use of a capacitor in a DC line)
2. Using a large series impedance (series regulator) to obstruct the flow of interference
3. Using a low shunt impedance (shunt regulator) to bypass interference to ground
4. Using an equal but opposite signal to cancel the original signal

Electrical devices such as capacitors and inductors do not store the sizable amounts of energy required for high power low frequency filters. There is also the difficulty of storing energy in the form of alternating current in resonant circuits. For example, whatever portion of the interference that cannot be stored and averaged out in a passive element must be prevented from passing through the active section of the filter. This is done either by providing a high impedance path to the interference signal (series regulator), shunting it to ground (shunt regulator), or canceling it by an opposing signal of the same magnitude. Active filters for a DC line may therefory contain capacitors as storage elements and modified series regulators to create a high impedance path, and modified shunt

regulators in combination with high gain feedback systems for cancellation. In the case of AC line filters, cancellation is a most effective way to minimize interference. In contrast to conventional regulators used in regulated power supplies, these filters must not regulate the amplitude of the power to be passed.

Examples of Active Filters

The following simplified examples typify the three filter requirements most often encountered and describe the basic operation and achievable performance for each filter type.

Example 1 - Inverter Filter: In industrial and military applications, DC/AC and DC/DC inverters ranging from watts to several hundred kilowatts are rapidly gaining widespread use. Their operation produces repetitive current fluctuations containing a broad frequency range with the first harmonic usually between 50 Hz and several kilohertz. Because of a finite DC power source impedance, corresponding voltage fluctuations are generated. These fluctuations propagate as interference throughout the system and may result in malfunctioning of associated susceptible electronic equipment. This is a case in which the interference path is opposite to that of the power and a given voltage attenuation is desired.

The voltage and current attenuations of a typical active filter for a DC/AC inverter are shown in Figure 14-14: the 1 kHz chopping frequency is voltage-attenuated by 40 dB. The circuit uses a storage capacitor in combination with a large series impedance element. With the power source impedance, an equivalent passive pi filter is formed by substituting a common-base transistor circuit for the inductor. When an AC voltage is applied between collector and ground (interference side), only a small fraction ($1/h_{rb}$) of this voltage appears across the external impedance connected between emitter and ground (filtered side). Capacitor C, presenting a shunt impedance, is required only when the interference source is a current rather than a voltage. From the h-parameter equivalent circuit, the following expressions can be derived for this type of filter:

$$\text{Voltage attenuation (dB)} = 20 \log_{10} \frac{1}{h_{rb}} \qquad (14\text{-}13)$$

$$\text{Current attenuation (dB)} = 20 \log_{10} \frac{|Z|}{\frac{1}{2\pi fC} h_{rb}} \qquad (14\text{-}14)$$

Wherein:

C	=	Capacity
Z	=	Power source impedance
f	=	Frequency of chopper
h_{rb}	=	Small-signal reverse voltage transfer ratio

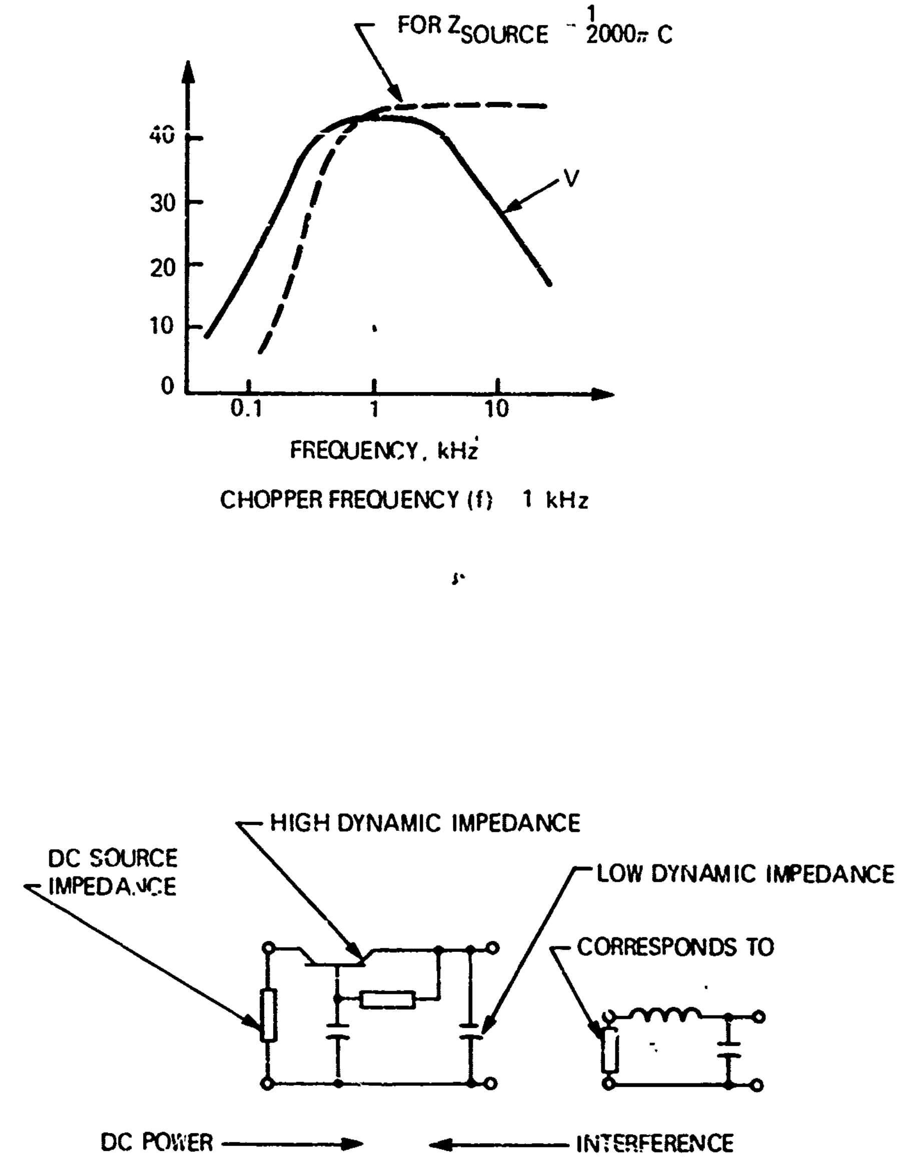


FIGURE 14-14 ACTIVE FILTER FOR A DC/AC INVERTER

Example 2 - Random Pulse Filter: Quite often one is faced with the problem of suppressing conducted EMI generated by random switching of many loads. For rectified power, filtering on the DC side is most effective. As in example 1, the interference path is in the opposite direction to the DC power. Here, current attenuation rather than voltage attenuation is generally required.

The random pulse filter employs the same underlying principle of the preceding example (storage capacitor and a large series impedance element). Because the attenuation requirement of this filter is higher and has to be maintained over a wide frequency range, typically 10 Hz to 100 kHz, a high gain trans-conductance amplifier is added to the circuit as shown in Figure 14-15. Interference current present at the emitter side of the pass transistor is attenuated by the closed-loop circuit. The attenuation is identical with the open-loop gain of the amplifier. The filter yields high current attenuation values, independent of the DC source impedance.

Limitations of pulse level, duration, repetition rate, and rise time have to be considered and must be specified for a given filter. The filter does not require an external power supply.

Example 3 - Interference Filters for Power Lines: Active AC power line interference filters pass, with high efficiency, only a narrow band about the power frequency. One of the prime applications is in connection with shielded room filtering where interference flowing in the same direction as the AC power has to be attenuated. Without sophisticated modifications, moderate voltage attenuation values, approximately 30 dB, are obtained even at very low load and source impedance levels; two filters may be cascaded for higher attenuation values. In modified switching-mode operation, a 60 dB insertion loss should be realized in one stage.

The power line filter shown in Figure 14-16 uses the principle of cancellation and, in very simple terms, operates as follows: the signal from the input is fed into an AC coupled amplifier through an adaptive notch filter, which is tuned to the fundamental of the power line frequency. The amplified interference signal, with opposite polarity, is returned in series to the source through the transformer. All signals except the fundamental are therefore attenuated by the gain of the amplifier. Within a limited range, a separate digital control circuit provides automatic tuning of the notch filter to power line frequency and corrects any changes in the filter itself. The voltage attenuation curve for a simple 220 volt, 20 ampere unit is shown in Figure 14-16 (b).

When inserted in the line, the filter introduces the equivalent of a small inductance of 700 μH for the pass frequency. The change in output voltage at full current rating caused by this inductance is negligible, i.e. 1 volt for a load power factor approaching unity and up to 6 volts in the worst case for zero power factor. The filter can handle an interference voltage of 80 volts peak to peak. This interference amplitude could be increased, but at the expense of efficiency. Efficiencies of 90 percent have been realized for 220 volt, 20 ampere filters.

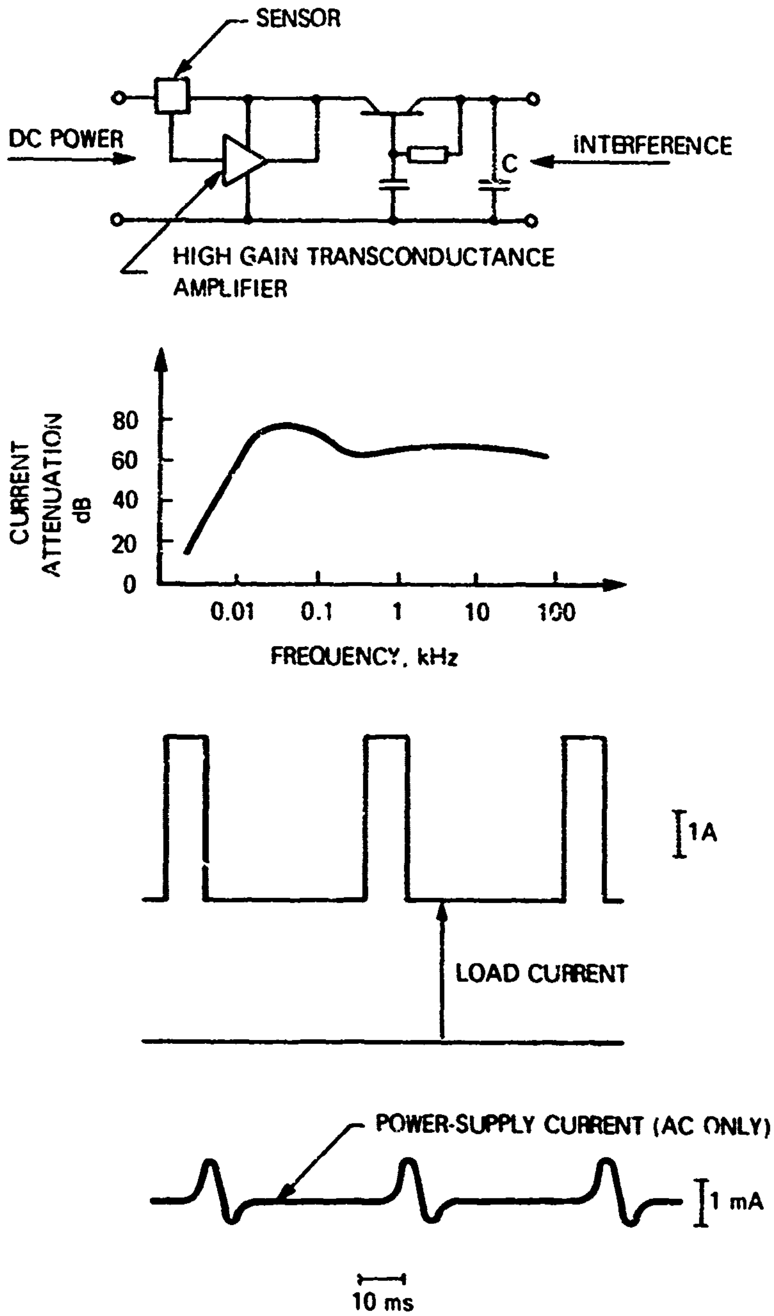
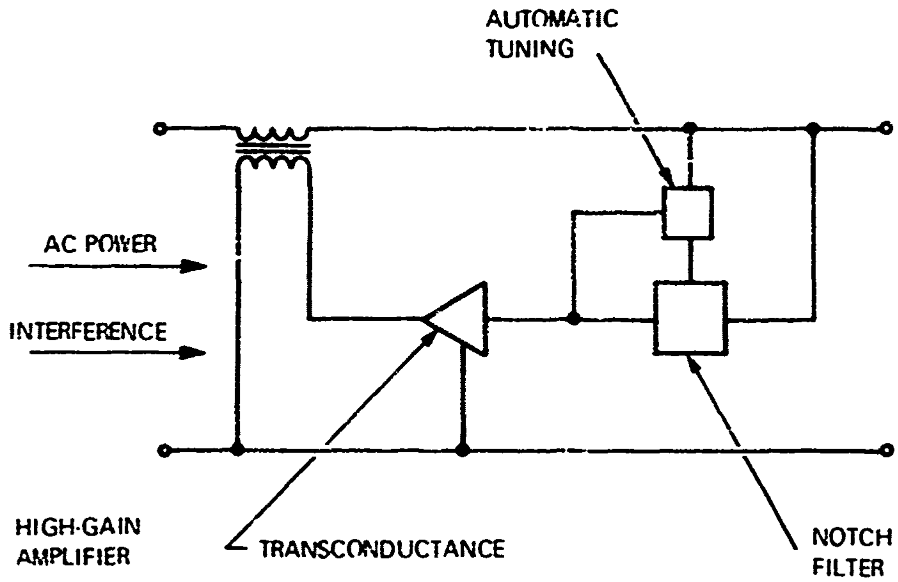
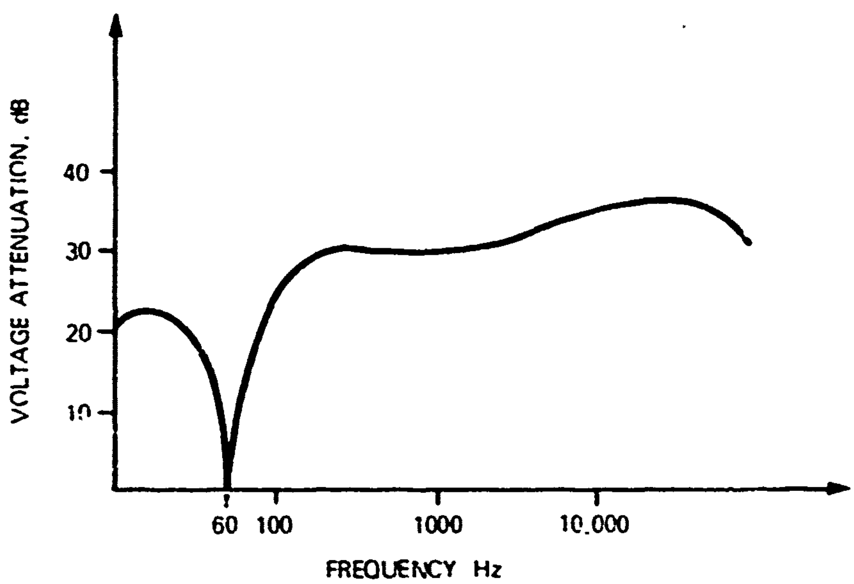


FIGURE 14-15 RANDOM PULSE FILTER



(a) Circuit Diagram



(b) Attenuation Characteristic

FIGURE 14-16 ACTIVE FILTER FOR POWERLINE INTERFERENCE

Example 4 - Q-multiplier Filter: For best selectivity, RF amplifiers should use high-Q circuits and amplifiers with high input and output resistance. The gain and selectivity of the input circuit can be increased by radio frequency Q multiplication using active circuit elements. A Q-multiplier is a stable regenerative stage that is connected in parallel with one of the RF or IF stages of a receiver to increase its capability to reject off-frequency interference. Figure 14-17 represents a typical configuration for regenerative action that uses the antenna coil L_1 as the feedback coil to make the Q-multiplier regenerative. This in effect adds a virtual negative resistance to L_2, thereby increasing the effective Q of the resonant circuit. A gain control for the Q-multiplier is provided to set the regeneration just below the point of oscillation for narrowest bandpass, or to a lesser degree of regeneration for wider bandpass. Thus the Q-multiplier can operate as a variable bandwidth filter.

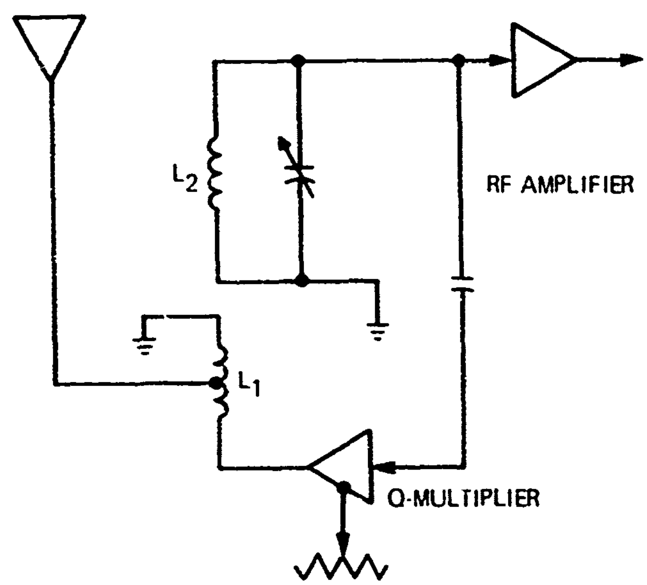


FIGURE 14-17 Q-MULTIPLIER RF SELECTIVITY FILTER

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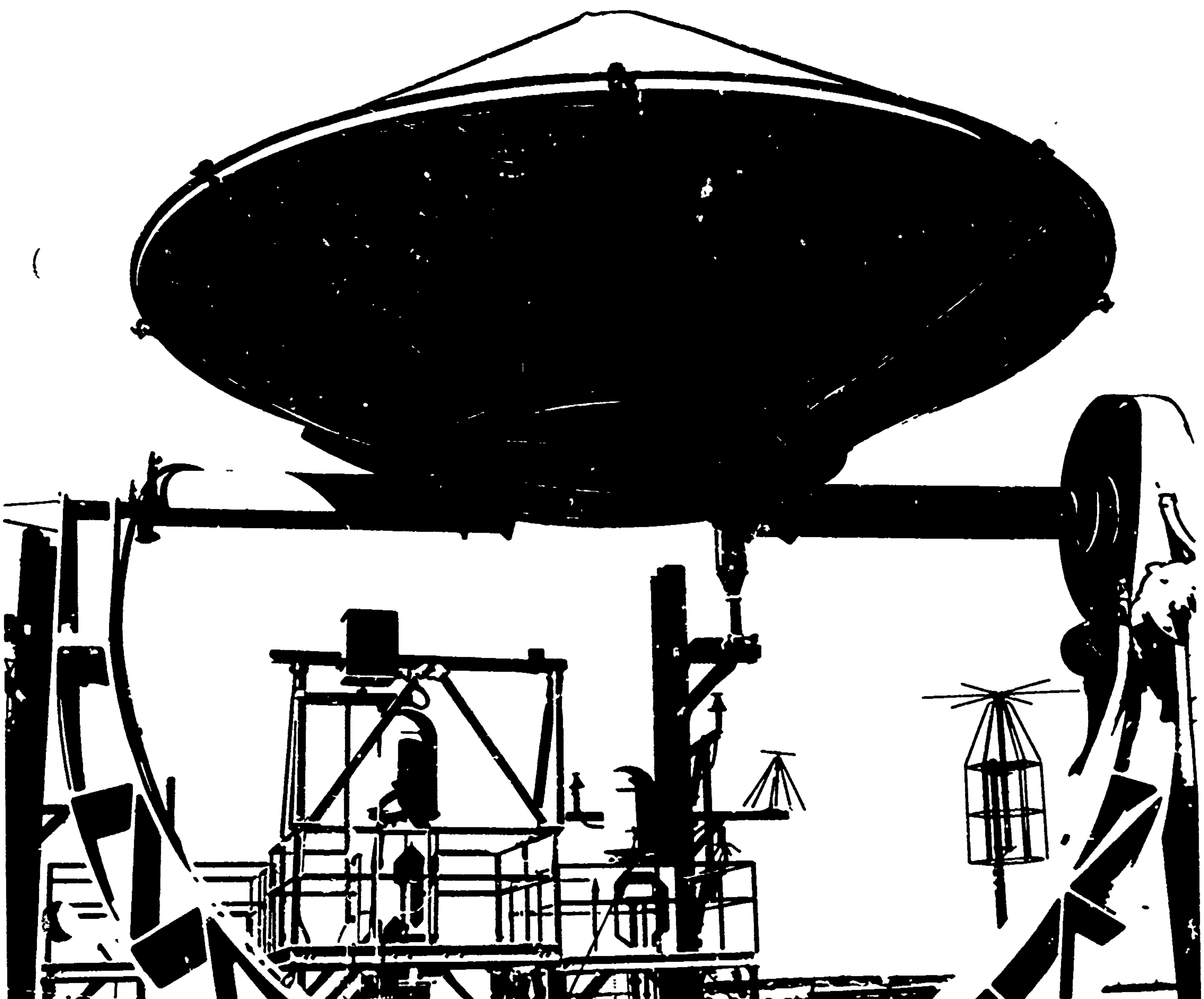
CHAPTER 15



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CHAPTER 15
ELECTROMAGNETIC CHARACTERISTICS OF ELECTRONIC PARTS, FUNCTIONAL CIRCUITS, AND COMPONENTS

CONTENTS

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CHAPTER 15

ELECTROMAGNETIC CHARACTERISTICS OF ELECTRONIC PARTS, FUNCTIONAL CIRCUITS, AND COMPONENTS

INTRODUCTION

Many electronic parts have characteristics that can influence electromagnetic compatibility. As density, complexity, and sensitivity of parts have increased tremendously in recent years, a number of heretofore negligible noise sources have become important causes of degradation and catastrophic failure of systems. The following sections describe EMC characteristics of many types of parts. Because a common current may flow in several parts, many effects commonly associated with one type of part may appear in other types.

PART CHARACTERISTICS, INTERFERENCE GENERATION, AND SUSCEPTIBILITY

RESISTORS

The major types of resistors are:

- Carbon composition
- Deposited carbon-composition film
- Pyrolytic carbon film
- Metal film
- Wirebound
- Microelectronic
- Special purpose

The resistor type to be used is determined by considerations of resistance, cost, wattage, compactness, precision, distributed capacitance, distributed inductance, life, and noise. Composition resistors may be of the pellet or the filament types. Composition resistors are made of finely divided carbon and a binder pressed into a slug with leads imbedded in each end. The slug is then enclosed in a phenolic case and the resistor body is molded. In some cases, the resistor is enclosed in a ceramic tube with cement over the ends. The filament type has the carbon and binder mixture coated on the outer surface of a glass tube and the

leads inserted into the tube. A phenolic tube is then molded around the resistor body.

Carbon or metal fixed film resistors are usually made by depositing a controllable-thickness resistive material in a continuous film onto a base. The resistor body is then covered with a plastic or epoxy. The geometry of film resistors enhances their high frequency characteristics so they are useful up to 400 MHz.

A microelectronic resistor is a thin layer of silicon on a base or metal over a semiconductor: close spacing increases capacitance and leakage, the small size limits available resistances, and undesired semiconductor junctions may be formed.

Any covering on the resistor body can act as a thermal barrier as well as protection against moisture, so dissipated energy is carried away primarily by the leads. Special metal jackets are made for helping heat energy to leave the resistor body. Bifilar winding of a wound resistor reduces inductance because adjacent turns carry currents in opposite directions. However, adjacent turns may have considerable potential difference, which causes the resistor to exhibit appreciable shunt capacity. Capacitive currents may have adverse effects for AC applications. The Ayrton-Perry winding is preferred, as each resistor is made up of two parallel windings in opposite directions so the turns cross each other at points of no potential difference. A typical Ayrton-Perry resistor wound on a cylindrical spool has one percent of the inductance of a conventional spool-wound power resistor.

A composition resistor can exhibit an AC resistance lower than its DC value. This characteristic is known as the "Boella effect" and is primarily due to the shunting effect of distributed capacitance that results from the large number of conducting particles mixed with dielectric material. To reduce this effect, resistors with a minimum of dielectric should be used so the dielectric constant and loss factors will be minimized. Decreasing the resistor cross-section and increasing the resistor length, as in the filment type of resistor, decreases the problem. Obviously, because of the greater amount of dielectric used, higher values of resistance have a greater percentage of change in value.

Skin effect, which occurs at high frequencies, causes the current flow to be concentrated at the surface with little of the current in the rest of the cross-section. Because current is not evenly distributed through the entire cross-section of the conductor, skin effect causes an increased effective resistance for RF over that of the DC value.

Table 15-1 shows the effect of radio frequency on resistance characteristics of some general-purpose axial lead carbon composition resistors of one megohm resistance value. The resistor produced by manufacturer A is described as a "hot molded fixed resistor." The resistance element is a carbon composition slug. Manufacturer B's resistor is made with a carbon composition film on a glass body. The manufacturer's published frequency characteristics include both inductance and capacitance effects.

The equivalent circuit for a resistor depends upon manufacturing processes,

Table 15-1. Ratio of Radio Frequency Resistance to Direct Current Resistance of a Resistor

(For axial lead carbon composition resistor, 1 Megohm)

Frequency	Manufacturer A			Manufacturer B		
	1/2 watt	1 watt	2 watt	1/4 watt	1/2 watt	1 watt
10 kHz	1.00	1.00	1.00	1.00	1.00	1.00
100 kHz	0.89	0.85	0.75	1.00	1.00	1.00
1 MHz	0.54	0.46	0.37	0.92	0.89	0.90
10 MHz	0.21	0.15	0.12	0.65	0.60	0.67
100 MHz	0.07	0.04	0.04	0.32	0.28	0.36

techniques, and raw materials. In general, at low frequencies and small di/dt changes, the equivalent circuit of a resistor is represented by Figure 15-1. Figure 15-2 is the equivalent circuit of a resistor near the return circuit and operating at a frequency where the C of the return circuit is significant and where distributed C is low. If it is a composition resistor, the inductance may be negligible.

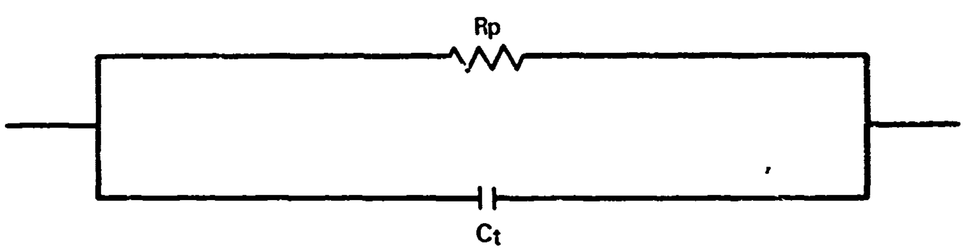


FIGURE 15-1 .SIMPLE EQUIVALENT CIRCUIT OF A RESISTOR

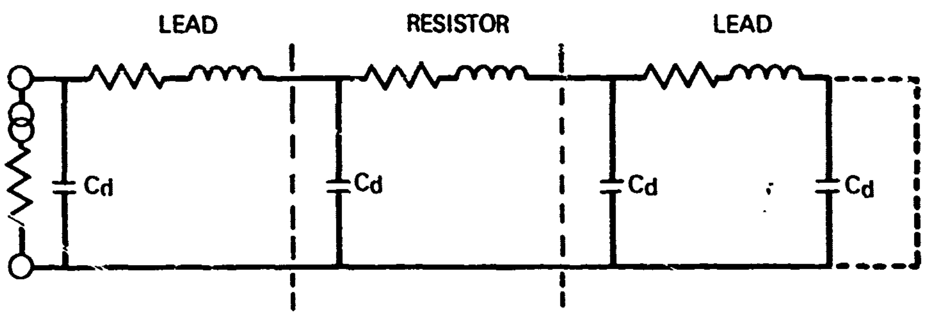


FIGURE 15-2 EQUIVALENT CIRCUIT OF A RESISTOR PLACED CLOSE TO THE RETURN PATH

Wirewound resistors have a relatively large distributed capacitance and inductance and are also affected by skin effect, exhibiting an increase in resistance as the frequency increases. The general circuit for a wirewound resistor is shown in Figure 15-3.

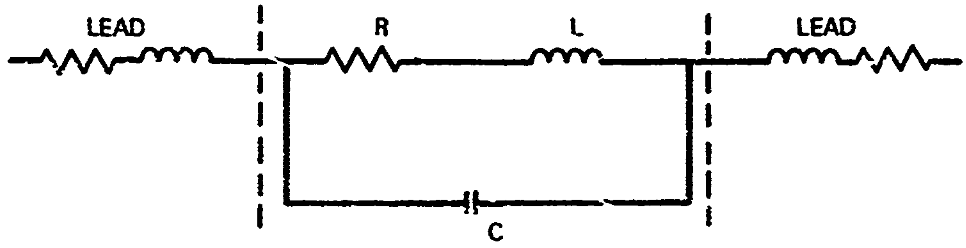


FIGURE 15-3 EQUIVALENT CIRCUIT OF A WIREWOUND RESISTOR

All resistors generate thermal and current noise. Thermal noise voltage is independent of frequency, as expressed by:

$$E_{th} = (4KTRB)^{1/2} \qquad (15\text{-}1)$$

where:

E_{th} = thermal noise voltage (rms)

K = Boltzmann's constant = 1.374×10^{-23} joules per °K

T = absolute temperature (°K)

R = resistance component affected by thermal agitation

B = noise bandwidth (Hertz)

This equation can be shown in graphical form as in Figure 15-4.

On the other hand, current noise is a function of frequency and type of resistor, so that an approximation is:

$$E_c \approx I(C/f)^{1/2} \qquad (15\text{-}2)$$

where:

E_c = rms voltage/Hz of bandwidth at frequency f

C = noise quality constant of proportionality

I = current through the resistor (DC and rms amperes) (15-2)

f = frequency (Hz)

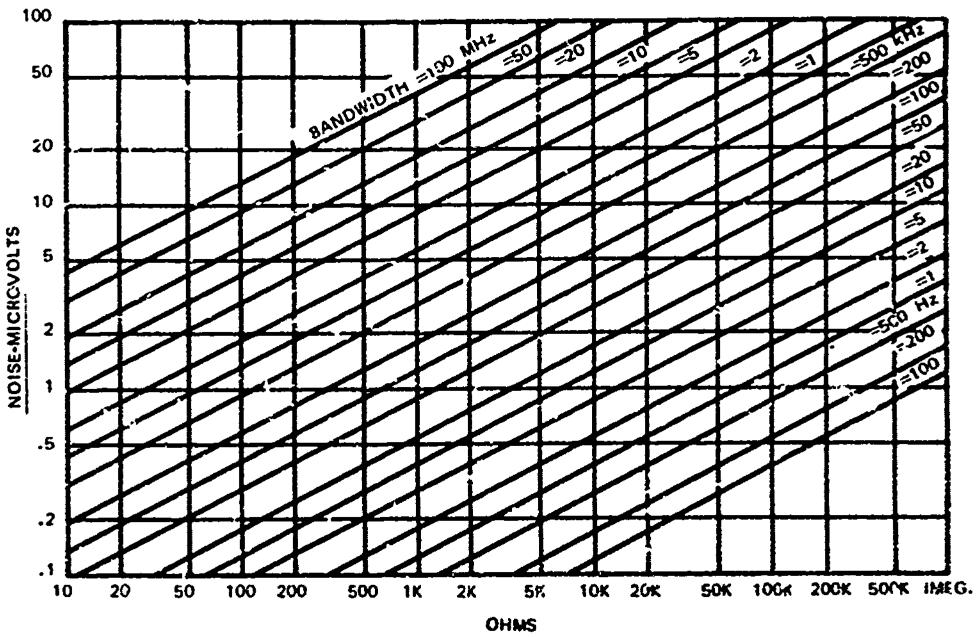


FIGURE 15-4 THERMAL NOISE VOLTAGE VS RESISTANCE FOR VARIOUS BANDWIDTHS (AT A TEMPERATURE OF 80 DEGREES FAHRENHEIT, FOR ALL RESISTORS)

Current noise varies as shown in Figure 15-5. To make this graph usable, the $\mu V/V$ scale must be multiplied by the voltage across the resistor. Current noise is generated in molded composition and metallized carbon resistors but usually not in wirewound and high-stability deposited-carbon resistors. The addition of noise sources is.

$$E_{total} = \left(E_{th}^2 + E_C^2\right)^{1/2} \qquad (15\text{-}3)$$

Table 15-2 shows that metal film and fixed wirewound resistors generate a lower noise level than other types, although damage or improper manufacturing processes can result in increased noise generation.

Up to approximately 10 GHz, proper spacing and short leads can minimize the effects of self and mutual inductance, while various capacitances and dielectric losses are negligible.

A conductor of uniform cross-section and diameter d, spaced distance D from a return circuit consisting of a conductor of the same dimensions, has an inductance, L, per unit length (henrys per inch) of:

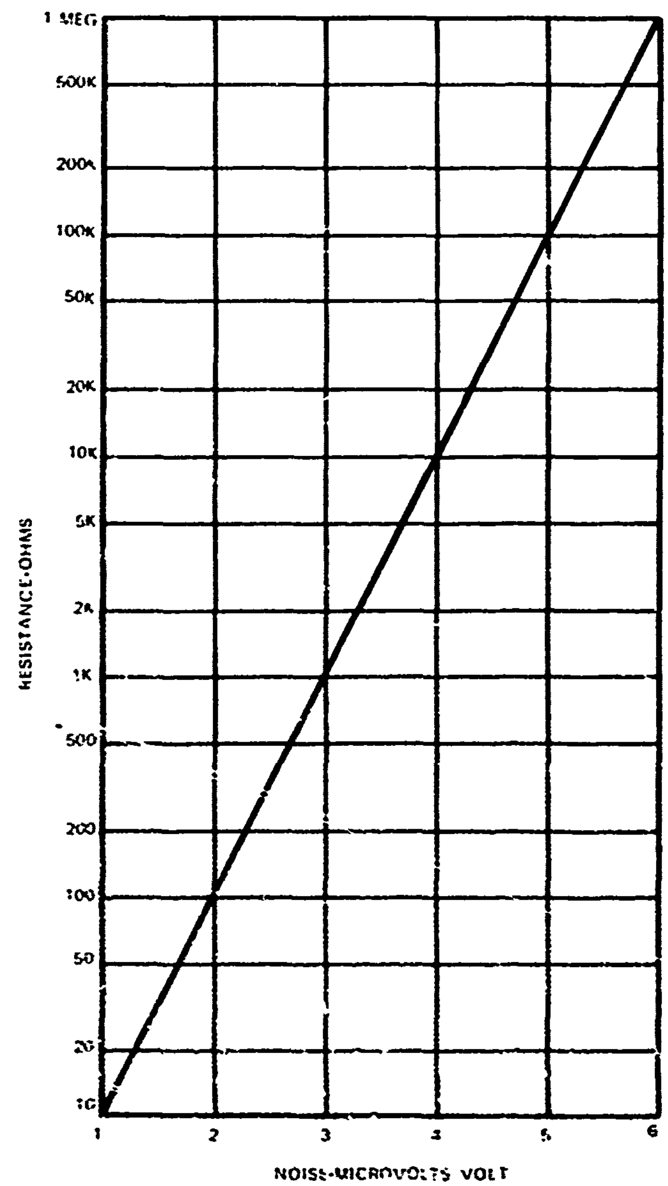


FIGURE 15-5 NOISE GENERATED WHEN A RESISTOR IS CARRYING CURRENT

$$L = 2.54\left(4 \ln \frac{D}{d} + 1\right) \times 10^{-9} \tag{15-4}$$

For sinusoidal current, the reactance (ohms per inch) is:

$$X = 16f\left(4 \ln \frac{D}{d} + 1\right) \times 10^{-9} \tag{15-5}$$

Table 15-2. Typical Resistor Noise Values

Typical Noise Values for 20 to 20,000 Hz Bandwidth	
Resistor Type	μV/V
Metal Film and Wirewound	0.001 to 0.082
Deposited Carbon	0.05 to 0.86
Composition	0.4 to 4.6

The following tabulation was calculated from the preceding equations for a 1-watt RC 32 resistor (9/16 inch long × 7/32 inch diameter outside dimensions, one manufacturer's form of construction) connected with one-half inch of lead on each end placed coaxially, and resistor and leads parallel to a return conductor. The calculation takes the effective resistor diameter as 5/32 inch, length 3/8 inch, lead length 1-3/16 inch, and takes the lead and return circuit each as 0.40 inch diameter, except for the approximation that the return conductor is 5/32 inch diameter for the 3/8 inch length opposite the resistor.

	Resistor Only		Contributed by Leads Only	
Spacing D (inches)	Inductance (μh)	Reactance at 10^6 Hz (milliohms)	Inductance (μh)	Reactance at 10^6 Hz (milliohms)
1/4	2.74×10^{-3}	17.2	20.9×10^{-3}	132
1	8.03×10^{-3}	50.3	35.3×10^{-3}	222
2	10.65×10^{-3}	66.8	42.9×10^{-3}	270

Between the body ends, the capacitance of a 1/2 watt resistor is about 0.1 to 0.5 pF and the inductance of the leads is effectively in series with the capacitance.

The inductance and capacitance of helical-form resistors can exhibit broadband effects and parallel resonance at particular frequencies. Therefore, these resistors are often limited to DC power frequencies, but proper design can use

the characteristics to filter pulses or undesired frequencies.

Strong electromagnetic fields can affect resistors, usually causing a change in resistance due to heating. Composition resistors exhibit only the heating effect whereas spiral film and ordinary wirewound resistors are also inductors which can couple energy into their circuits.

Variable resistor noise may be due to several reasons:

1. Foreign materials formed on the resistance element due to wiper abrasion,
2. Dust particles or chemical contamination,
3. Formation of oxide films on contact surfaces,
4. Mechanical untrueness,
5. Triboelectric effect from the wiper sliding on the element, causing a self-generated voltage,
6. Thermoelectric effect from external or frictional heat.

Noise can be generated when high current densities exist at the wiper-to-element interface, such as that which occurs when a wiper makes contact with the high spots on the surface of a composition or a ceramic carbon metal (cera-met) element. Due to heating, the contact may change quickly, often producing arcing and white noise. The wirewound variable resistor wiper can make or break contact with adjacent turns and cause small arcs. In precision variable resistors, the noise level can be held down to 100 millivolts or less.

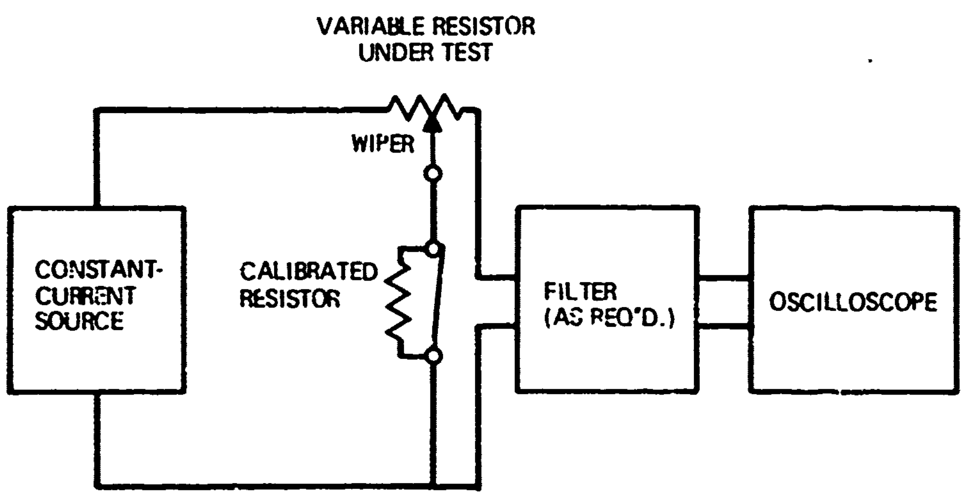


FIGURE 15-6 CONVENTIONAL VARIABLE RESISTOR NOISE MEASUREMENT CIRCUIT

The conventional noise-measuring circuit is shown in Figure 15-6. The filters are used if the variable resistor has to be checked over a limited bandwidth for a particular application. Table 15-3, showing noise voltage, was generated by using a DC to 50 kHz oscilloscope as shown in Figure 15-6.

Table 15-3. Variable Resistor Noise Voltage

Resistance	Current		
	1 ma	0.1 ma	0.01 ma
1k	0.01 to 0.03V	0.002V	0.0002V
10k	0.15 to 0.25	0.02	0.002
100k	1.0 to 4.0	0.3	0.035

Table 15-4 illustrates some of the common resistor EMC situations Usual EMC problems involving resistors are:

Interference Generation	Susceptibility
Thermal noise	Boella effect
Current noise	Skin effect
Faulty construction	Resonant frequencies
Faulty connections	Radiation

CAPACITORS

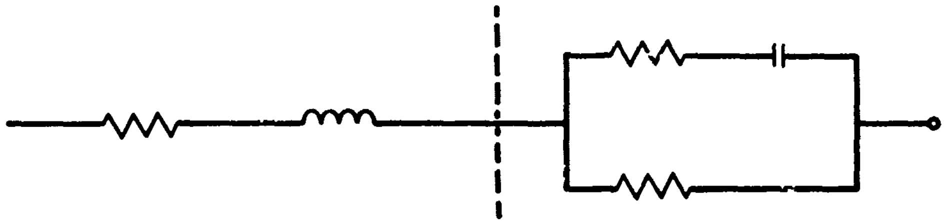
The approximate lumped characteristic equivalent circuit of most capacitors over a wide frequency range is shown in Figure 15-7. Figure 15-8 is the equivalent circuit of electrolytic capacitors.

In most capacitors, the inductance acts with the capacitance to give a terminal impedance, which generally is minimal at the resonant frequency and increases on either side of this frequency. Inductance and series resistance limit the rate of change at times of sudden charge or discharge. The series resistance affects the dissipation factor and may cause problems in AC, high-precision, and timing circuits. For most applications, series resistance may be considered to be constant and independent of frequency. Shunt conductance is caused by current leakage and voltage stress across the dielectric. Current leakage is usually small in solid dielectrics, but may be a problem in high-precision capacitors as well as some electrolytic capacitors. Shunt conductance is affected by both the instantaneous and longer-duration application of a voltage stress. The effects are energy

Table 15-4. Effects of Resistor Characteristics

Resistor Characteristics	Example	Problem
Direct end-to-end capacitance	Attenuator	High-frequency signals fed through to a point not grounded for the signal frequency.
Total capacitance (end-to-end and lead-to-ground)	Feedback amplifier plate load resistor	Phase shift to signal components as a function of frequency
Resistance varies with frequency	Some amplifiers; some measurement methods	Boella and skin effects.
Inductance	Shunt resistors in attenuators	Change of effective impedance with frequency. Important in low resistance resistors below 100 MHz.
Inductance	Any resistor	Phase shift, change of effective impedance. Important above 100 MHz.
Susceptibility to RF fields	Composition and metal film resistors	Can change resistance and overheat
Susceptibility to RF fields	Ordinary spiral wound resistors	Induced voltage, proportional to the numbers of turns and field strength, is transferred to circuitry.

loss, heating, and change in power factor. Absorption of energy results in reappearance of voltage on the capacitor after it has been discharged and not recharged. Dielectric absorption causes a voltage stress that is delayed because of the time required to displace charges from the dielectric. In high voltage circuits, a means of discharging capacitors should be provided to prevent danger to personnel. The resonant frequency is determined by many factors, including physi-



WHERE

R_S SERIES RESISTANCE
R_D DISSIPATION FACTOR
L – INDUCTANCE OF LEADS & WINDINGS
R_P – RESISTANCE DUE TO DIELECTRIC
C IDEAL CAPACITANCE

FIGURE 15-7 LUMPED EQUIVALENT CIRCUIT OF MOST CAPACITORS OVER A WIDE FREQUENCY RANGE

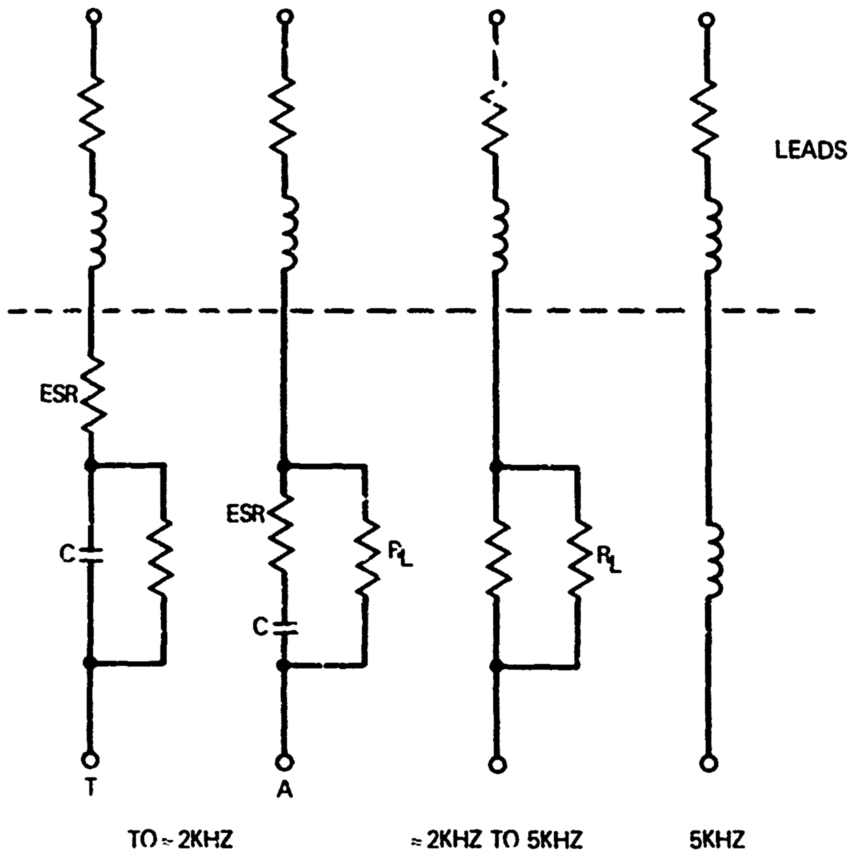


FIGURE 15-8 LUMPED EQUIVALENT CIRCUIT
FIGURE 15-8 LUMPED EQUIVALENT CIRCUIT OF ELECTROLYTIC CAPACITORS

cal size, dielectric properties, capacitance, lead inductance, and inductance of the plates. Figure 15-9 shows lead length effects. Three types of resonances can occur in disc-type capacitors:

1. Low-frequency resonance due to long leads
2. Medium-high frequency resonance when discs are connected in parallel, due to internal leads
3. High-frequency resonance due to resonant cavity effects in high dielectric effect capacitors

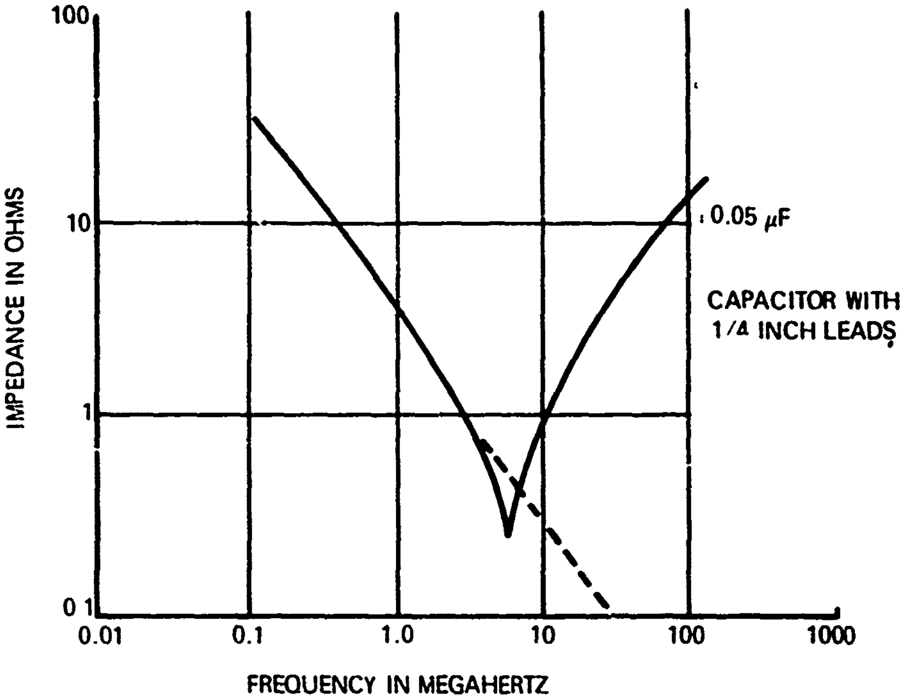


FIGURE 15-9 TYPICAL EFFECT OF LEAD LENGTH

Ceramic dielectric capacitors and filters using the ceramic (barium titanate) dielectric are attractive because of their small size and low weight when compared with capacitors using more conventional materials such as paper or mica However, the characteristics of the ceramic capacitors must be investigated carefully before a choice is made for a specific application. Some ceramic capacitors are extremely sensitive to temperature, so there can be a significant degradation in equipment performance if a ceramic capacitor is used as a bypass operating at a local temperature of –40°C or at an elevated temperature of +100°C. For example, a nominal 1000 pF ceramic disc feed-through type capacitor, will, according to one manufacturer's specifications, have a capacity of 330 pF at –40°C. While the operating temperature range is –55° to +85°C, the capacity is stated for a temperature of 20°C ± 1°C. Likewise, the continuous working

voltage rating is 500 volts DC but the capacity is stated for the 0.5 to 5.0 volt range. With 500 volts applied and a feedthrough current of 25 amperes, the effective attenuation as a bypass capacitor is reduced by 20 dB at +25°C. The design engineer must be sure that he has considered the most extreme conditions of operation when he specifies a capacitor or filter incorporating a ceramic dielectric.

Tantalum capacitors also offer attractive space and weight savings under some conditions of operation. The design engineer must be aware of the limitations of the various types of tantalum capacitors: solid, foil, and wet anode.

Solid slug tantalum capacitors are made by sintering. This forms a spongy slug of metal that has a large effective surface area and is extremely small for its capacity and voltage rating. Feed-through capacitors of the solid tantalum type are effective up to 5 GHz.

Foil type tantalum capacitors can be made in voltage ratings up to 300 volts as compared with about 50 volts for the solid and 125 volts for the wet type. The foil type is limited to audio frequency and low radio frequency applications because of high internal inductance. Sometimes a tantalum foil capacitor is shunted with a smaller paper or ceramic capacitor to extend the effective bypass range.

The original wet type tantalum capacitor has fallen into disuse because of the danger of electrolyte leakage. In the newer wet type construction, the electrolyte is a gel and the danger of leakage and consequent corrosion is no longer a factor. The wet type construction offers the smallest size and the largest capacity of all tantalum types.

The tantalum capacitor has a further advantage in that low-temperature performance is greatly superior to the aluminum electrolytic type. Tantalum capacitors also have longer shelf life and less current leakage especially at high temperatures and after long periods of idle time.

The total inductance of a capacitor is the sum of the internal electrode inductance and the external lead inductance. The following values are typical of internal (electrode) inductance for various types of capacitors. They apply generally to that particular type of capacitor regardless of value.

Porcelain and ceramic fixed capacitors	0.0014 μH
Wet-anode tantalum capacitors	0.025 μH
Solid tantalum capacitors	0.020 μH
Foil tantalum, tubular case, with leads	0.050 μH
Foil tantalum, rectangular case, lug terminals	0.023 μH

The external (lead) inductance, L, can be determined from this expression for the self-inductance of a straight round copper wire:

$$L = 5.08 \times 10^{-3} \ell \left(2.303 \log_{10} \frac{4\ell}{d} - 0.75\right) \mu H \qquad (15\text{-}6)$$

where:

ℓ = lead length in inches

d = lead diameter in inches

Where the leads are 22 gauge wire (0.025" diameter), the lead inductance will be:

0.0037 μH for 1/4" total lead length

0.0093 μH for 1/2" total lead length

0.022 μH for 1" total lead length

In a given capacitor installation, if the internal and external inductance are added to determine the total inductance, the resonant frequency, f_R, of the combined inductance and capacitance can be found using the expression:

$$f_R = (39.44LC)^{-1/2} \quad (15\text{-}7)$$

where:

L = the effective inductance (internal and external)

C = the effective capacity

Table 15-5 shows various EMC problems with capacitors.

Usual EMC problems involving capacitors are:

Interference Generation	Susceptibility
Dielectric breakdown	Resonant frequencies
Flutter or scintillation	Radiation
Dielectric charge or discharge	
Polymerization	
Radiation	
Mechanical problems	

INDUCTORS

An inductor can be a portion of a conductor and its return, a single conductor coil, or usually, a multiturn coil. An inductor has inductance, resistance, capacitance between turns, and capacitance between turns and ground, shields, and other circuits. An aircore inductor may be wound on a non-magnetic core, whereas magnetic cores are made with steel or iron alloy in sheet, strip, wire, or powder form.

The distributed capacitance acts as a lumped shunt capacitance, resulting in

a parallel resonance frequency for the inductor. Other characteristics are power dissipation or loss, saturation, susceptibility to and generation of stray fields, and instability of its characteristics. High-precision circuitry can lose appreciable precision and stability when temperature and humidity cause dielectric losses from the insulation and support of the inductors.

Table 15-5. EMI Problems in Capacitors, Causes and Cures

Type of Noise	Cause(s)	Result and Cure
Internal spike	Combination of temperature and voltage stresses causing breakdown of dielectric	Permanent damage to most capacitors; stress should be decreased, probably by using several capacitors in series. Self-healing capacitors like foil tantalum might help
Random noise in RF capacitors, e.g., silver-mica, silver-ceramic	Flutter or scintillation caused by random and sudden change in capacitance due to improper adhesion of silver to the dielectric, allowing intermittency	Some areas of the capacitor are out of the circuit; proper manufacture will avoid this
Electrolytic capacitor scintillation	Voltage surges greater than working voltage or exceeding temperature rating	Keep voltage sources and the temperature below the ratings
Noise pulses during charging and discharging at very low frequencies	Release of dielectric stress, particularly with polystyrene and quartz dielectrics	Avoid low frequency use of polystyrene and quartz dielectrics; liquid dielectrics may minimize effect
Noise pulses	Plastic dielectrics such as polyethylene continue to polymerize even after being put in use. Stresses eventually cause noise pulses	Use other dielectrics

Table 15-5. (Continued)

Type of Noise	Cause(s)	Result and Cure
Possible noise in polyethylene, quartz and mica dielectric capacitors (particularly small capacitance units)	Light, radioactive particles, and X-rays produce ionic action on the dielectric	Shielding or other means
Passing or absorption of energy at certain frequencies	Resonant frequency caused by capacitance, inductance, and physical qualities	Proper design and shielding
Effective inductance of leads is too large even with short leads	Leads of capacitor behave as inductors	Use parallel capacitors connected by short conductors with the return as close as possible to the other conductor: use coax conductors or a flat-strap conductor close to the return conductor

Current flowing through a coil causes flux lines that produce an EMF proportional to the rate of change of flux linkage. The self-inductance is:

$$L = N\phi I \qquad (15\text{-}8)$$

where:

L = self-inductance (henrys)

N = number of turns, loops, or linkages

ϕ = magnetic flux (webers)

I = current (amperes)

Mutual inductance (inductive coupling) occurs when magnetic flux lines of one element link with another element. Energy is thereby coupled from one element to another and can cause interference with other circuits. Mutual coupling decreases with distance, and the least coupling occurs when the inductor axes are at right angles.

Inductors are often shielded to keep their electric and magnetic fields within a limited space around the inductor. Electrostatic shields can be made of low electrical resistance material such as copper, aluminum, or zinc. These shields prevent magnetic flux from passing through because voltages are induced that set up eddy currents that oppose the magnetic fields. A high-permeability material such as Permalloy is used at low frequencies if the flux is unidirectional. The use of high-permeability material results in an induced opposing magnetic field and a magnetic flux short circuit so there will be a negligible magnetic field outside of the shield. Saturation of the shield reduces its permeability so that the shield is

Table 15-6. EMI Problems in Inductors, Causes and Cures

Problem	Possible Cause	Cure
Passing or stopping desired signals	Resonance due to inductive, capacitive, and resistive characteristics	Design and shielding
Power dissipation over the ratings	Skin effect, conductor resistance, eddy current and hysteresis losses	Use of stranded conductors, non-magnetic cores and toroidal geometry winding
Varying effective inductance	Distributed capacitance in coil causes apparent decrease in inductance	Minimize distributed capacitance and/or permit high eddy current effect to reduce effective inductances
Interference by mutual inductance	Proximity of two coils, one coil and a conductor, or any two circuit elements	Separation, shielding or keeping object axes at right angles
Transients	Current applied or cut off to the inductor	Same as for electromagnetic relays (see Section on Relays)

no longer a short circuit to the flux.

Table 15-6 shows some of the EMC problems encountered with inductors. Usual EMC problems involving inductors are:

Interference Generation	Susceptibility
Coupling	Skin effect
Counter-EMF on switching	Core saturation
"Ringing" on transients	Resonant frequencies
	Mutual inductance

RELAYS

A relay is a device that permits one or more circuits to be switched by electrical variations in a usually independent control circuit. Relays can be of several types: electromagnetic, saturable reactor, bimetallic, semiconductor, photosensor, and others. There are many designs available, depending upon switching to be performed, power source, number and type of contacts, and cost.

The most common relay is the electromagnetic solenoid. EMC problems occur in both the actuator and contact circuits. The electromagnetic solenoid has large inductance due to the large number of turns and iron mass in the core and armature. When the coil circuit current is interrupted, the collapse of the magnetic field generates a voltage equal to L(di/dt). This potential can reach 10 to 100 times the supply voltage in a few microseconds, and then decay at a rate determined by the inductance, distributed capacitance, and resistance of the winding circuit. The high amplitude voltage surge has a steep wave front that can cause arcing at the point of interruption, along with broadband signals capable of causing interference or damage to other circuits. EMI effects of an AC relay are variable because the voltage and current are continually changing in magnitude, producing results according to the state at the time of switching.

Abrupt changes in circuit current will produce waveforms that cause EMI. Ideal contact operation occurs when the contacts go from fully open to fully closed or vice-versa without arcing. In actual practice, when contacts close, they bounce and form a closure followed by one or more openings and reclosures. In small relays, a single bounce may occur 10 to 50 microseconds after the initial closure and final closure in a few more microseconds. In large relays, the bounce may be repeated several times at intervals of a few milliseconds. In any case, contact interruptions can cause broadband di/dt and dv/dt changes that generate EMI. Arcing can occur when contacts are first opened, continuing until contact spacing is too large to maintain the arc (depending upon the surrounding gas and the applied voltage). The make and break of a contact arc when opening a circuit is proportional to the instantaneous supply voltage, the circuit inductance, and the rate at which the contacts separate. EMI may be worse for contact closure than for contact opening. Closed contacts can open or vary in contact resist-

ance due to shock, acceleration, or vibration, causing arcing or at least circuit current changes. If required, contact arc suppression can be used.

Suppression of large voltage surges caused by interruption of the coil current can be effected by:

1. A capacitor and small series resistance in shunt with the coil.
2. A resistor in shunt with the coil.
3. A parallel resistive winding on the coil core.
4. A diode reverse-biased to the line voltage in series with a small resistor, all in shunt with the coil.
5. Parallel back-to-back diodes across the coil.
6. Zener or avalanche diodes in shunt with the coil.

Relay contact arcs in DC circuits can be suppressed by:

1. A capacitor in shunt with the contacts.
2. A capacitor and a series resistor in shunt with the contacts.
3. A capacitor and series diode in shunt with the contacts.
4. A capacitor in series with a parallel combination of a resistor and diode in shunt with the contacts.

A relatively new method of suppressing inductive transients is by use of a Thyrector diode, a selenium rectifier that acts much like back-to-back zener diodes.

Contact bouncing and erratic opening in digital systems cause data to become erratic. Polar or latching relays are therefore often used in such systems. A polar relay, once actuated in a given direction, will remain latched on its internal permanent magnet until its state is reversed by current in the opposite direction.

In Figure 15-10, the suppression circuit will limit the voltage surge to:

$$e_o = I_{dc}(L_1/C_1)^{1/2} \qquad (15\text{-}9)$$

when R_L is negligible. C_1 is usually 0.1 to 1.0 μF with a voltage rating of approximately 15 times the maximum DC input. The use of a capacitor alone will result in a large charging current, damaging the switch contacts or causing noise current surges, so the resistor is necessary. R_1 should be:

$$R_1 = V_{dc\ in}/I_{max\ desired} \qquad (15\text{-}10)$$

where the maximum desired current should be limited to 10 times the normal coil operating current. The network will appear resistive at all frequencies if:

$$R_L = R_1 = (L_1/C_1)^{1/2} \qquad (15\text{-}11)$$

This circuit will affect contact opening and closing times only slightly.

A resistor in shunt with the coil results in power consumption whenever power is applied to the coil. It also affects the dropout time and may result in an extreme widening of the differential.

The circuit of Figure 15-11 results in a polarity-sensitive relay. When the switch is closed, the diode is effectively an open circuit so it does not affect the circuit. When the switch is opened, the collapsing magnetic field in the inductance develops a reverse voltage and current flows through the diode, the voltage being limited to the forward diode voltage drop due to the internal resistance of the diode and the voltage drop across resistor R_1. The peak inverse voltage (PIV) rating of the diode should be higher than the maximum input voltage or any transient voltages, and should include a sufficient safety factor. Most germanium diodes exhibit a lower forward resistance and voltage drop so they minimize the magnitude of the interference voltage, but silicon diodes are usually used because of cost, current ratings, and high PIV considerations. When R_1 is greater than the effective forward resistance of the diode, the resistor becomes the primary suppressor and the diode acts as a one-way switch so the resistor will not consume power all the time the coil is energized. This circuit provides a small voltage backswing, but there is an increased dropout time such that

$$\text{Dropout Time Constant} = \frac{L_1}{R_1 + R_L} \qquad (15\text{-}12)$$

R_1 must be selected to provide the desired voltage back-swing. Using a pull-down voltage on the diode will increase the backswing but decrease the dropout time.

Back-to-back zener diodes, as in Figure 15-12, are effective on AC as well as DC circuits. When the switch is opened, the high voltage causes one of the diodes to break down due to the zener effect, and the voltage surge is limited. This method is a compromise between the RC network and the single diode for backswing magnitude and dropout time.

Suppression is required for relays located in an area that has susceptible equipment. Enclosures or consoles for relay circuitry should minimize susceptibility and propagation. Power and signal leads must be isolated, twisted, or shielded to avoid coupling. Filters should be used on conductors as necessary at points of entry into the enclosure. If necessary, signal circuits over 50 kHz

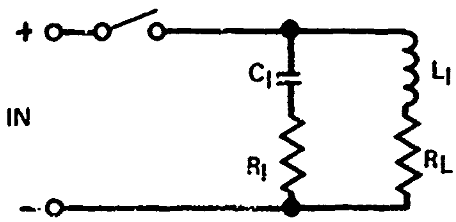


FIGURE 15-10 USE OF CAPACITOR AND RESISTOR FOR INTERFERENCE SUPPRESSION.

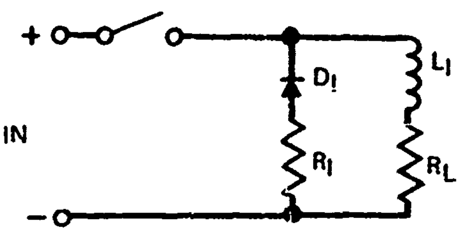


FIGURE 15-11 USE OF A SINGLE DIODES FOR INTERFERENCE SUPPRESSION.

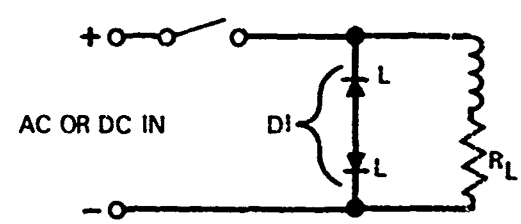


FIGURE 15-12 USE OF BACK-TO-BACK DIODES FOR INTERFERENCE SUPPRESSION

should be shielded and the shields grounded upon entering and leaving components. Signal circuits below 50 kHz can be shielded with single-point grounding. Shielding and grounding are more fully discussed in Chapters 11 and 12. Transient suppression by the use of extra components introduces the problem of decrease in system reliability and added weight, space, and cost. Table 15-7 illustrates some of the common problems with relays. Usual EMC problems involving relays are:

Table 15-7. EMI Problems in Relays, Causes and Cures

Problem	Cause	Cure
Generation and su[illegible] propagated EMI	Relay circuit characteristics	Twist, shield, and filter power leads and enclosing relay in metal shield
Simultaneous problems in coil and contact circuits	Movement of the armature causes coil magnetic circuit changes and varying contact di/dt and dv/dt	Proper relay circuitry design, including filtering
Relay contacts generate EMI when they should be quiescent	Vibration	Proper relay design or contact circuit suppression
Noise, misoperation, or permanent damage in semi-conductors	Inductive circuit causes large voltages	Components must be properly rated and/or di/dt and dv/dt must be diverted or suppressed
Low frequency interference in the signal circuitry	Low frequency spurious voltages	Single-point grounding and twisted leads
High frequency interference in the signal circuitry	High frequency spurious voltages	Multiple-point grounding

Interference Generation	Susceptibility
Magnetic effects of actuator circuit	Mutual inductance
Contact switching transients	Core saturation
Radiation through coil and leads	Magnetic field sources

INSULATORS

The primary reasons for EMI caused by insulation are surface tracking (discharge of electricity across the insulators), corona (luminous discharge caused by ionization of the air), and internal breakdown. The primary means of avoiding problems are by:

1. The use of generous clearance and creepage distances
2. Protection from dirt, moisture, and overheating
3. The use of dense, smooth, and homogeneous material
4. The use of dielectric material according to the frequency used

The failure of organic-material insulators results in carbonization and combustion. Inorganic insulator failure results in a change to metal oxides with a negative temperature coefficient so that thermal cycling will cause sharp changes in current, as well as overheating, mechanical cracking, arc-over, and even catastrophic failure. Resistors that are wound or deposited on ceramic bodies, probably coated with a vitreous glaze, and even those molded with inorganic fillers can have the inorganic insulator failure characteristics. Some typical insulator problems are shown in Table 15-8. Usual EMC problems involving insulators are:

Interference Generation	Susceptibility
Surface tracking	Contamination
Corona	Ionization
Internal breakdown	Voltage

CONDUCTORS

A conductor is any material which, when subjected to a difference in potential, permits an electric current to flow. It is usually convenient to use a metal such as copper as the conductor in an electronic circuit. Copper is inexpensive and relatively stable in the ambient temperature range usually encountered. It is easily soldered but will corrode on exposure to the atmosphere. For this reason it is sometimes protected with a plating or coating of tin, silver, or gold.

The selection of conductor size is generally related to voltage drop in the conductor or heating effect by power loss. In the radio frequency spectrum, skin effect must be considered. "Skin effect" is the term for an uneven cross-sectional distribution of current density so that there is a concentration of current near the surface or skin of a conductor. This leads to a higher resistance of

Table 15-8. EMI Problems in Insulators, Causes and Cures

Problem	Cause	Preventive Measure
Surface tracking causing di/dt charges which produce wide band of frequencies that can cause EMI	Surface contamination, chemical degradation of insulation, momentary overvoltage	Protection from contamination, use of proper material, proper voltage design
Surface tracking resulting in catastrophic degradation	Low impedance discharge circuit releasing high energy	Protection from contamination, use of proper material, proper voltage design
Surface tracking with small but relatively persistent EMI	High impedance discharge circuit which limits energy to circuit component tolerances	Protection from contamination, use of proper material, proper voltage design
Glow discharge which may be visible and audible but causing electrical noise because of di/dt generation	Corona with high voltage across one conductor to ground or to another conductor	Prevention of voids within insulators, protection from contamination, prevention of sharp points at high potentials, low voltage gradient design

that conductor to current in the radio frequency range. Litzendraht or "litz" wire was designed to offset the skin effect. It is composed of several strands of enamel-coated wire, individually insulated, interwoven, and connected in parallel at each end. Its effectiveness can be accurately analyzed in relation to skin depth in the individual wires. As this general effect, combined with the effect of flux linkages between the conductor and its return, is examined for higher frequencies, it becomes apparent that at somewhere around 1 to 10 gigahertz, conduction within a solid conductor becomes difficult. In this range, a transition is made to waveguide for signal transmission. Waveguide is effective up to about 100 GHz.

Skin effect can be offset by other means. Since a circular cross-section conductor has the least skin surface per unit of area, it may be advantageous to make the conductor square or rectangular. Flat, strap type conductors have inherently lower AC resistance because of their greater surface for a given cross-section area.

Alternatively, removing the center area of the conductor and creating a hollow tube will significantly reduce the self-inductance of the conductors. For this reason, tubular conductors are commonly used in ground systems and in high-power transmitters.

Parallel wiring systems may be loaded up to a point where the wire fuses or where corona is probable, whereas arcing is the power limiter in coaxial and waveguide systems. In general, parallel lines have less loss than equivalent coaxial lines, while coaxial lines have less radiation. Shielded wire is also relatively more expensive. The attenuation of shields is due to energy reflection at the boundary and absorption as signals pass through. A typical voltage measurement between an external pick-up wire and the central conductor of a coaxial line shows a pick-up ratio of about 1 to 1000. The use of a double shield increases the attenuation by about 25 dB, and critical circuits may require even more shields.

Braided sleeving is sometimes used as a bond strap because its flexibility makes it convenient to use as a bonding lead across a vibration mount. However, because of its construction, it has a higher inherent inductance than a strap made of solid copper sheet. Braided sleeving also makes a convenient cable shield. For this use it has a limited effectiveness; for low frequency an overall insulating cover should be used so that the braid can be grounded at one point and insulated from ground throughout the rest of its length. As a high frequency circuit shield it can be left bare, except that when it is unprotected the eventual corrosion between intersecting strands will degrade the shielding effectiveness.

In many ways teflon is an ideal insulating material for wires in cables. It offers a high insulation with good mechanical protection in extremely thin coatings on conductors. This allows a high density of wire within a cable. This in turn may increase problems with circuit-to-circuit coupling within a cable because closer spacing means greater magnetic and capacitive coupling. Capacitive coupling is a function of the distance between conductors and the length of the conductors with a third important factor, the dielectric constant of the material between the conductors. Air has a dielectric constant of 1.0 while teflon has a dielectric constant of 2.1. This means that capacity will increase by a factor of 2.1 when the air between two electrodes is replaced with teflon. The dielectric constants at 1.0 MHz of other common dielectrics are given below:

Polyethylene	2.26
Polyvinyl chloride	3.52
Paper	2.99
Nylon	3.14
Water	78.2

Water was included in the list to show why a small amount of moisture can upset an electronic circuit.

Various methods to minimize interference are:

1. When two conductors with similar current levels are twisted together,

the field generated by one tends to cancel the field of the other if the currents are opposite in direction. The greater the number of twists at a constant rate, the more effective is the cancellation of the magnetic fields.

2. Multiple-conductor cables that bundle a conductor with its return conductor that is carrying current in the opposite direction causes magnetic-field cancellation. The amount of cancellation depends upon the relative equality of the currents and the spacing between conductors.

3. A conductor surrounded by a shield, as in a coaxial cable, theoretically will not have an external magnetic field. Various factors degrading this are the lack of solidity of the surrounding conductor and its conductivity.

4. Skin effect, at higher frequencies, can have an increasing effect on the electric and magnetic fields. At higher frequencies, hollow conductors should be considered to minimize external fields.

5. Magnetic shields can be used to minimize magnetic fields. Eddy currents that occur in grounded shields create absorption losses that minimize the external magnetic field. The absorption losses (in dB), A, are

$$A = 15.35\, t(fg\mu)^{1/2} \tag{15-13}$$

where:

t = thickness of the shield (mils)

f = signal frequency (Hertz)

g = shield material conductivity relative to copper

μ = shield material magnetic permeability relative to free space

6. Bare conductors operating at high-voltage potentials can produce large electrostatic fields at sharp corners or points that ionize the surrounding atmosphere, resulting in a broadband white noise corona. Minimum bend radius for a high-voltage conductor should be 10 times its outside diameter and connection points and other irregularities should be rounded. Contamination across a component can also lead to corona by reducing the required breakdown potential.

7. Conducted interference can be limited by coating the conductor with high-permeability material which magnifies skin effect losses. There is a large effect in the approximate frequency range of 25 kHz to 50 MHz.

8. Ferrite beads are usually tiny cylindrical beads that may be strung on a wire to increase inductance of the wire and thereby cause attenuation of signals. Attenuation by inductive reactance and I^2R losses is a function of frequency because there is no DC current in the bead. As an example, 4 beads can increase the inductance of a two-inch piece of wire by fifteen times and can cause a 6 dB attenuation over a very wide frequency range. The cost is less than that of resistors or RF chokes.

9. Single-point shielding must prevent the shield from touching ground at more than one point. A common remedy is to enclose a coaxial conductor in a plastic sheath.

10. Ionic atmosphere, created by field gradients in the region of conductance, can promote the deterioration of the insulation or shielding and eventually result in a change from the original characteristics.

Figure 15-13 shows a comparison of coaxial, twisted, and Litz-type cables.

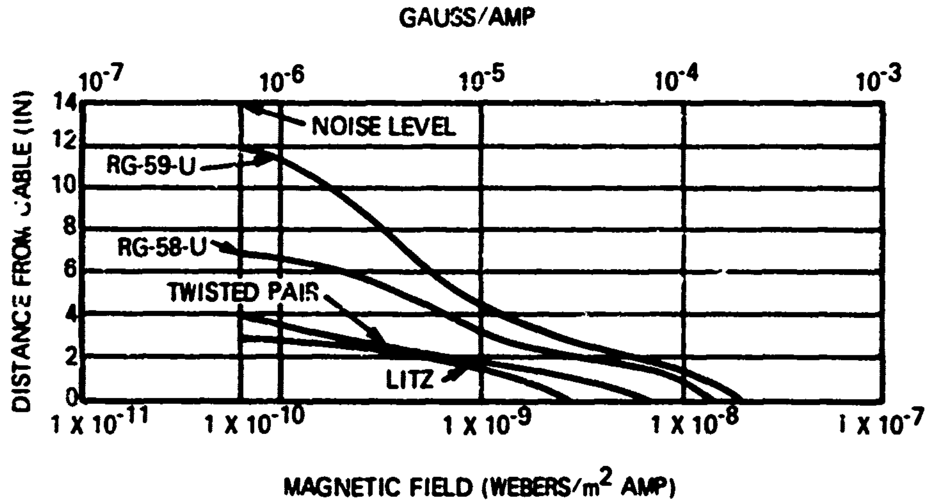


FIGURE 15-13 MAGNETIC FIELD FROM CABLES AT 1 kHz AS A FUNCTION OF DISTANCE FROM THE CABLES

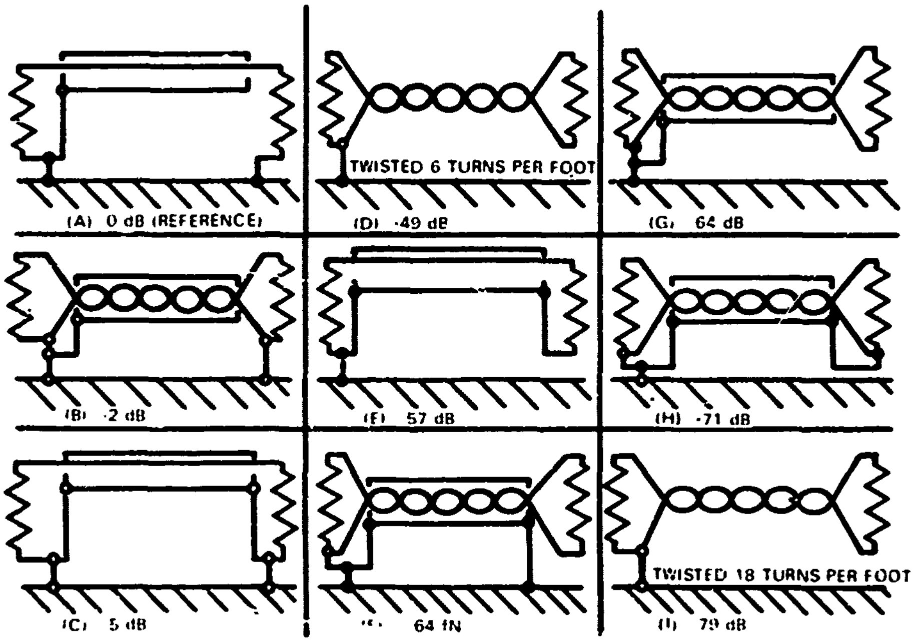
Figure 15-14 shows a comparison of conductor susceptibility to low-frequency (approximately 100 kHz) EMI.

Usual EMC problems involving conductors are:

Interference Generation	Susceptibility
Electric fields	Skin effect
Magnetic fields	Magnetic fields
Radiation	Induced signals
Thermal noise	
Improper connections	
Geometric discontinuities	
Conductive coupling	

TRANSISTORS

Transistors have many advantages over vacuum tubes. Some advantages are



*PREFERRED CIRCUIT FOR HIGH FREQUENCIES

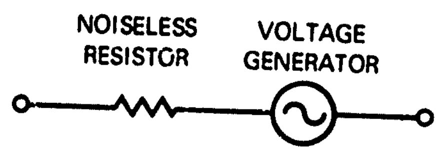
VALUES GIVEN ARE FOR CIRCUITS 1 INCH ABOVE GROUND PLANE BUT ARE ABOUT THE SAME FOR OTHER DISTANCES FROM GROUND PLANE.

FIGURE 15-14 RELATIVE SUSCEPTIBILITY OF CIRCUITS TO MAGNETIC INTERFERENCE

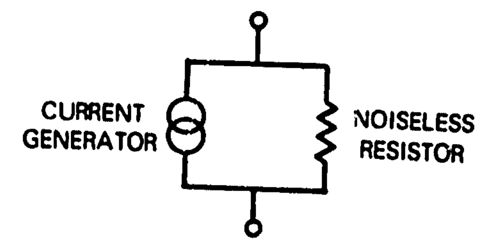
small size and weight, relatively low power operation, increased reliability, and no heater or filament power requirement.

Low level operation can be a problem with regard to sensitivity to interference signals and possible destruction. Inherent semiconductor noise limits the minimum detectable and amplifiable signals. Internal resistance and capacitance or transit time limits the maximum amplifiable frequency. All noise generated by a transistor will appear at the output, but it may be possible to minimize the effects. The three main types of noise a transistor generates are thermal, shot, and flicker noises.

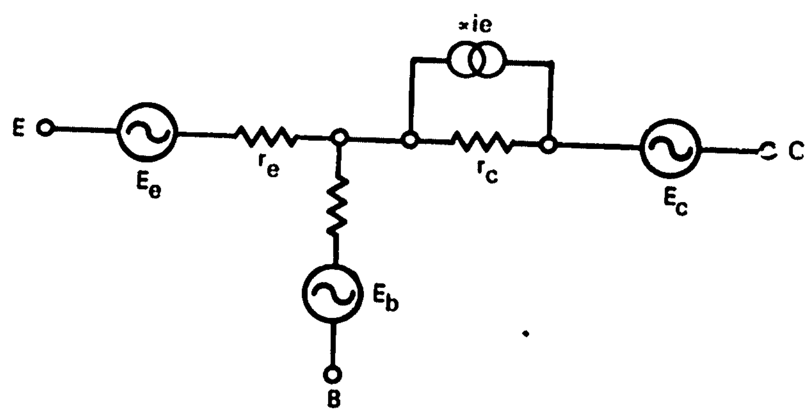
Thermal noise in transistors is believed due to thermal agitation causing random motion of electrons and holes in the material. The equivalent circuit of a thermal noise source can be represented by a voltage generator in series with a noiseless resistor as shown in Figure 15-15(a). The internal noise has a flat frequency spectrum (white noise) and the amount of output noise power is limited by the circuit bandwidth to which the noise source is connected. The noise spectrum is uniform throughout the frequency range until capacitance causes attenuation due to a drop in transistor gain. As an example of thermal noise magnitude, 6.4 microvolts can be developed across a 0.5 megohm resistance for a bandwidth of 5 kHz at room temperature.



(a) EQUIVALENT CIRCUIT OF THERMAL
NO NOISE SOURCE



(b) EQUIVALENT CIRCUIT OF
SHOT NOISE SOURCE



(c) EQUIVALENT NOISE CIRCUIT OF A TRANSISTOR

FIGURE 15-15 EQUIVALENT NOISE CIRCUITS

A constant-current generator in parallel with a noiseless resistor represents an equivalent shot noise source circuit as shown in Figure 15-15(b). Shot noise is generated by random movement of minority carriers across a junction whenever current is flowing. The current is not uniform due to the random diffusion of minority carriers as well as the random recombination and generation of charges. Shot noise has a flat (white noise) spectrum and is proportional to the number of minority carriers, current flow, temperature, and bandwidth, so that:

$$I_{sh}^2 = 2\,eIB \qquad (15\text{-}14)$$

where:

I_{sh}^2 = rms shot noise current (amperes)

e = election charge (1.6×10^{-19} coulomb)

I = DC current (amperes)

B = bandwidth (Hertz)

Flicker noise is called "1/f noise" because it has a power spectrum proportional to 1/f so that, for a given bandwidth, the noise decreases when the frequency is increased. It is also called "semiconductor noise" and is believed due to crystal imperfections and surface effects, including trapping of carriers by surface charges with associated surface and internal leakage.

$$E = \frac{KI^2B}{f} \qquad (15\text{-}15)$$

where:

E = mean square voltage

K = a constant of proportionality

I = DC current (amperes)

B = bandwidth (Hertz)

f = frequency (Hertz)

As can be seen in Figure 15-16, flicker noise (1/f) is usually predominant up to a frequency between 1 and 10 kHz, when thermal and shot (white) noise become predominant. An arrangement of all noise generators in a transistor is shown in Figure 15-15(c).

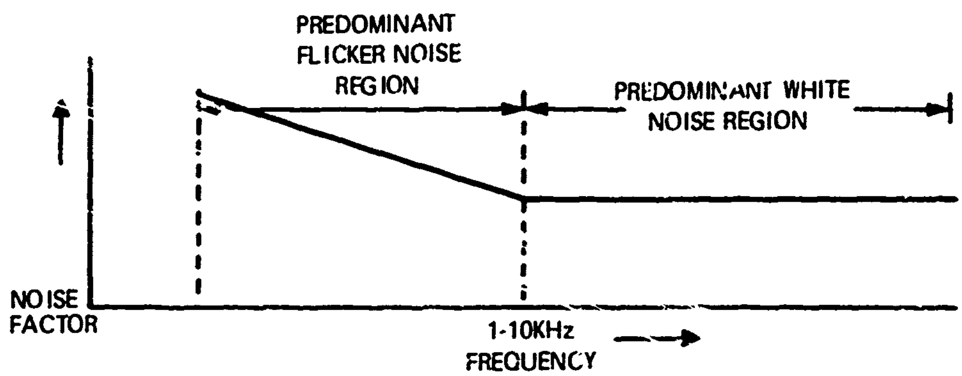


FIGURE 15-16 TYPICAL TRANSISTOR NOISE VERSUS FREQUENCY

In addition to the previous types of noise, amplifying transistors with high frequency capabilities (about 100 MHz or greater) may oscillate at spurious frequencies when operated considerably below (approximately 20 percent, by rule of thumb) the device capability. A transistor having usable current gain at 400 MHz, but operated as an amplifier handling frequencies below 80 MHz, tends to react with stray capacitance and inductance within the associated circuitry to oscillate parasitically at unpredictable frequencies. The form is usually that of wideband gaussian noise near or below the operating frequency. The parasitic oscillation is affected by interelement (junction) capacitances which vary, varacter fashion, over a wide range with changes of element voltage.

Transistors operated in a proportional-control mode usually will not introduce major interference. When used in a switching mode, they can introduce rapid changes in current in the supply and signal lines, and can potentially cause oscillations with fundamental frequencies around 250 kHz and 2 MHz. Inverters may cause serious interference in the range of 15 to 180 MHz with a peak around 60 MHz. Milliampere devices can have switching times in the order of nanoseconds while those of high amperage rating devices can be a few microseconds. Thus, the current gradient can be millions of amperes per second. "Soft switching" is a design that controls the rate of change of current, as well as selecting proper dimensions and carrier densities. To minimize interference, it is best to generate required pulses in the required location rather than sending them through long lines, thereby possibly multiplying the number of susceptible components involved. Waveform control techniques can also be used to make devices responsive to only certain pulse characteristics.

Low level transistors can be very susceptible to erroneous, or false, triggering caused by undesirable signals. The average silicon-controlled-rectifier (SCR) and many other four-layer semiconductor devices will turn on if a forward voltage with a high dv/dt is applied to the anode; the rapid internal capacitance charging causes a current flow that is similar to a gate turn-on signal. The typical dv/dt characteristic of one 35-amp (rms max.) SCR is 210 volts/microseconds at 80°C junction temperature. The dv/dt susceptibility can be minimized by various

circuit techniques, as well as temperature limitation.

Usual EMC problems involving transistors are:

Interference Generation	Susceptibility
Thermal noise	Radiation
Shot noise	Erroneous signals
Flicker noise	Magnetic fields
Resonant frequency oscillation	Temperature
Switching transients	Nonlinear characteristics
Spurious frequencies	

DIODES

Inasmuch as solid-state diodes are also semiconductors, they share many of the characteristics of transistors.

Under conditions of forward bias, a solid-state semiconductor stores a certain amount of charge in the form of minority current carriers in the depletion region. If the diode is then reverse-biased, it conducts heavily in the reverse direction until all of the stored charge has been removed. The resulting conditions are presented in Figure 15-17. The duration, amplitude, and configuration of the recovery time (also called switching time or period) pulse is a function of the diode characteristics and circuit parameters. These current spikes can generate a broad spectrum of conducted radio interference frequencies.

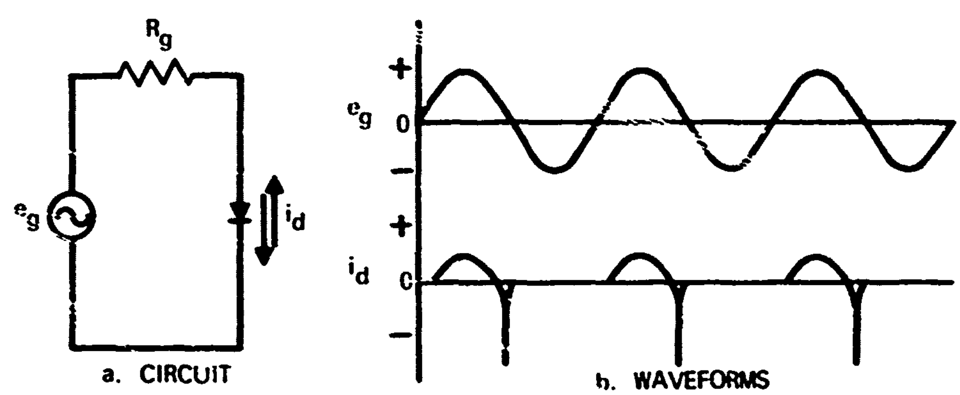


FIGURE 15-17 DIODE RECOVERY PERIODS AND SPIKES

Rectification involves switching from conduction to cutoff repetitively, causing di/dt rates dependent upon the input frequency, minority carrier storage in the diode, and the circuit characteristics. The interference effect can be minimized by one or more of the following measures:

1. Placing a bypass capacitor in parallel with each rectifier diode
2. Placing a resistor in series with each rectifier diode
3. Placing an RF bypass capacitor to ground from one or both sides of each rectifier diode
4. Operating the rectifier diodes well below their rated current capability

The ripple filter that normally follows a rectifier should not be relied upon to filter out the interference effect. The usual large-value capacitors used for ripple filters exhibit too much series inductance to function effectively as RF interference filters.

Diodes are also used to switch at a particular voltage level. The switching action results in rapid di/dt changes. Diodes are used as limiters to cut off a certain input waveform at a certain level. The greater the amount of limiting, the greater will be the number of spurious frequencies that occur due to steepening waveform. These switching actions can result in interaction with other components, distributed or actual impedances, and discontinuities.

Several design considerations to minimize switching interference are:

1. Operate at lowest possible voltages and currents
2. Anticipate diode-to-diode variation of characteristics
3. Use the lowest possible switching rate and amplitude
4. Select diodes with high working and peak inverse voltages
5. Use diodes with a slow recovery time (inherent with larger current ratings)

RF voltage can change the bias of a diode, resulting in improper switching, distortion, or improper output. All diodes are subject to reverse breakdown if they pick up RF voltages greater than their reverse breakdown voltages. Low power devices (generally those rated 25 mW or less) and small junction devices such as point-contact diodes operating in the vicinity of a strong RF field can absorb sufficient radiated energy to be degraded or burned out. Large junction diodes have a large junction capacitance, of the order of 10 to 15 pF, which will pass high frequencies. If this energy, added to the normal energy, exceeds the thermal limit of the device, damage can occur. Therefore, diodes subjected to RF fields should be shielded.

When used as an amplifier, a tunnel diode may couple with related circuitry inductance or capacitance to produce undesired oscillations, usually above 1 MHz. The oscillations should be suppressed by circuit design methods. All zeners generate shot and 1/f noise, but the noise level is higher in alloy zeners than in zeners made by a diffusion process. Generally, the noise increases with an increase in current but the noise may occur at some point on the zener curve and not at others (this noise is called "spotty"). Most commercial zener diodes have above 1 to 1000 microvolts of noise over a decade of frequencies.

Diodes with mechanical imperfections may generate noise when physically agitated. Such diodes may not cause trouble if used in a vibration-free environment.

Usual EMC problems involving diodes are:

Interference Generation	Susceptibility
Switching transients	Erroneous signals
Internal charge	Radiation
Harmonic distortion	Magnetic fields
Inherent noise	Temperature
Mechanical imperfections	Nonlinear characteristics

ELECTRON TUBES

EMC problems with electron tubes and their circuits are similar to those with transistors, differing primarily because of power levels and a greater number of elements as well as greater spacing between the elements.

Although ordinary vacuum tubes operating in the proportional-control or switching modes have EMC characteristics similar to those of transistors, gaseous conduction tubes (e.g., thyratron and ignitron) are quite different. The ignitor in an ignitron can be a source of noise because it acts like a spark-producing device. When a gaseous conduction tube is conducting, the space between anode and cathode contains a plasma that can oscillate by itself because of internal instabilities.

The principal types of tube noise are:

1. Shot effect
2. Partition noise
3. Induced noise
4. Gas noise
5. Secondary emission noise
6. Flicker effect

Shot noise (also called Schottky noise or Schot noise) is due to the random fluctuations in the rate of electron emission from the cathode. When the cathode temperature is the current flow limiting factor, the shot noise component is:

$$i_{sh}^2 = 2 e I_b B \qquad (15\text{-}16)$$

where:

i_{sh} = rms noise current (amperes)

e = electron charge (1.6×10^{-19} coulomb)

I_b = average plate current (amperes)

B = bandwidth (Hertz)

When the plate current is limited by the space charge, many of the fluctuations in the plate current are reduced due to the smoothing effect of the reservoir of electrons in the virtual cathode set up by the space charge. In this case, the following approximations can be used. For diodes:

$$i_{sh}^2 = 4K(0.64)T_c gB \tag{15-17}$$

and for negative grid triodes:

$$i_{sh}^2 = 4K(0.64/\sigma)T_c g_m B \tag{15-18}$$

where:

i_{sh} = rms noise current (amperes)

K = Boltzmann's constant (1.38×10^{-23} Joule/degree K)

T_c = cathode temperature (degrees K)

g = diode plate conductance (mhos)

g_m = triode transconductance (mhos)

σ = tube parameter (between 0.5 and 1.0)

B = bandwidth (Hertz)

The shot effect noise of a triode can be expressed by considering a resistance which, if applied to the driving grid of a noiseless tube as a source of thermal noise, would produce the same anode current noise component as is actually present. For triode tubes, the equivalent noise resistance (R_{eq}) is equal to $2.5/g_m$. In amplifiers, the noise voltage generated by R_{eq} is considered to be applied in series with the grid as shown in Figure 15-18. In this case:

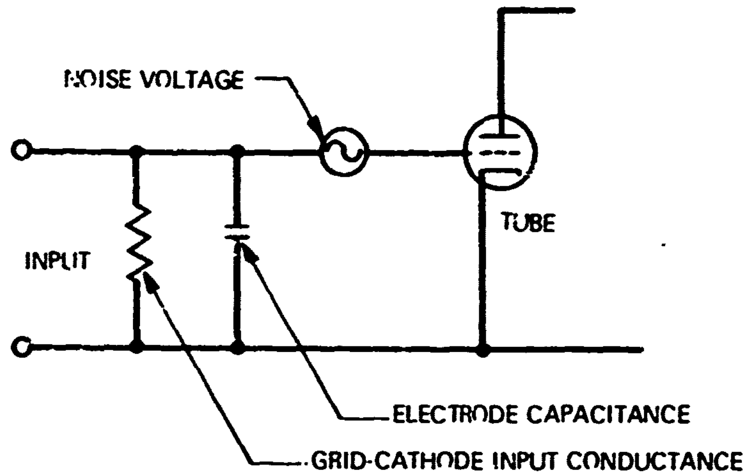
$$e^2 = 4KT_c R_{eq} B \tag{15-19}$$

where: (15-18)

e = noise voltage (rms volts)

R_{eq} = equivalent grid noise resistance

$$\bar{e}^2 = 4K\,TR_{eq}\,\Delta f$$



$\bar{e}$ - RMS VALUE OF NOISE VOLTAGE
K - BOLTZMANN'S CONSTANT
T - TEMPERATURE IN DEGREES KELVIN
Req - EQUIVALENT GRID NOISE RESISTANCE
Δf - BANDWIDTH IN CYCLES

FIGURE 15-18 EQUIVALENT CIRCUIT REPRESENTING PLATE-CURRENT NOISE BY A GENERATOR IN SERIES WITH A TUBE GRID

Partition noise occurs in multicollector tubes and is due to fluctuations in the division of current between the electrodes. The noise of a negative-grid pentode amplifier is represented by the equivalent grid resistance (R_{eq}), approximated by:

$$R_{eq} = \frac{I_b}{I_b + I_{c_2}}\left(\frac{2.5}{g_m} + \frac{20 I_{c_2}}{g_m^2}\right) \qquad (15\text{-}20)$$

where:

I_b = dc plate current (amperes)

I_{c_2} = dc screen current (amperes)

g_m = transconductance (mhos)

The values of R_{eq} of pentodes are usually three to ten times as great as those of comparable negative-grid triodes. Electron wave tubes, such as traveling-wave tubes, also exhibit partition noise.

At very high frequencies (over 30 MHz), fluctuations in the number of electrons passing a negative grid will induce noise currents. Increasing with frequency, the noise currents will be introduced into the input circuitry by electronic conductance.

Gas noise is produced by erratic motion of gas molecules in gas or vacuum tubes. Ionization by collision produces noise when ionized gas atoms or molecules liberate bursts of electrons when they strike the cathode.

Secondary emission noise is due to fluctuations in the rate of the production of secondary electrons.

Flicker noise, more common in oxide-coated cathodes, varies as 1/f and is caused by a low-frequency variation in cathode activity.

Some EMC problems involving electron tubes are shown in Table 15-9. Usual EMC problems involving electron tubes are:

Interference Generation	Susceptibility
Shot effect	Nonlinear characteristics
Partition noise	Conductive coupling
Induced noise	Magnetic fields
Gas noise	Radiation
Secondary emission noise	Resonant frequencies
Switching transients	Vibration
Local or parasitic oscillations	
Microphonic effect	
Hum	
Improper contacts	

SWITCHES

The function of an electrical switch is to interrupt the flow or change the routing of an electrical current. An electrical switch causes the impedance of a

Table 15-9. EMI Problems in Electron Tubes, Causes and Cures

Problem	Cause	Cure
Shot effect	Random fluctuations in the rate of emission of electrons from the cathode	Proper design
Partition noise	Fluctuation in the division of current between electrodes	If important, use tubes with fewer elements
Induced noise	At very high frequencies, fluctuations in the number of electrons passing a negative control grid induces noise currents	Use tube with better grid geometry
Gas noise	Ionization by collision of ionized gas striking the cathode, liberating bursts of electrons	Proper design or use of other electronic components
Secondary emission noise	Fluctuations in the rate of secondary electron production	Proper design or use of other electronic components
Flicker noise	Inversely proportional to frequency: due to a low-frequency variation in cathode activity; more common in oxide-coated cathodes	Avoid oxide-coated cathodes
Microphonic effect (vibration of socket with or without sound emanation),	Shock or vibration changes element spacing and damped mechanical oscillation causes changes in plate current, usually setting up vibration through the tube socket or by means of sound waves	Reduce by use of ruggedized tubes

Table 15-9. (Continued)

Problem	Cause	Cure
Hum	Use of AC for filament and heater-type tubes	Use DC, use hum-bucking circuits, use balanced filament supply, bias cathodes negative with respect to filaments.
Other tube noise	Leakage from the grid to another electrode, particularly a positive electrode; improper contacts (particularly with low level signals)	Tube replacement or ensure mechanically and electrically good contacts
Large number of unwanted frequencies at amplifier output	Caused by possible feeding in of unwanted frequencies compounded with operation on the non-linear portion of the characteristic curve	Proper design and shielding of the grid circuit
Interfering signals in an RF field	Pick up of RF signals through tube envelopes	Use tube shields
Affected by nuclear radiation	Causes change in tube characteristics	Use of ceramic tubes
Noise current in catcher of klystron amplifier	Electron beam passing through the catcher causes noise current in the shunt impedance of the catcher	Proper design for minimum effect

circuit to change rapidly between a relatively low value and some vary large value. The rapid change cause a high di/dt and dv/dt in the switched circuit which, in turn, produces steps in current or voltage waveforms capable of causing interference. Additional discussion of switching appears in the section on Relays

When a power circuit is switched by mechanical contacts, high frequencies that can cause interference are generated during both closing and opening of the contacts. As the contacts close, a step function of voltage is applied to the circuit which excites it, causing oscillations involving reactive elements. In addition, the step function itself contains high-frequency components. EMI is thereby generated that can be transmitted by radiation or conduction. The larger the wattage of the load being switched, the more difficult and expensive it becomes to control the effects of EMI.

Mechanical contacts have the additional problem of contact bounce when closing. Random opening and closing of the contacts chops the current, generating high-frequency oscillations and harmonic components. For inductive circuits, abrupt interruptions can lead to high induced voltage transients, contact arcing, dielectric breakdown, and associated phenomena. All may cause EMI problems.

The making or breaking of an electrical circuit by a mechanical switch is usually accompanied by the generation of an arc at the switch contacts. Arcing during normal operation of a switch occurs because a highly-ionized gas is substituted for a part of the metallic circuit as the switch contacts move apart. The arc is extinguished when the energy stored in the circuit is dissipated, including oscillation with distributed reactances, once the switch contacts exceed the arc-over distance.

An arc is a phenomenon that dissipates energy that is either supplied to or stored in an electrical circuit. The arcing phenomenon causes deterioration of contact surfaces where the arc is formed, which may destroy the contacts if continued. The arcing phenomenon is also a prime source of interference with a wide frequency spectrum.

Energy dissipated in an arc depends upon the circuit loads being switched. The most common types of loads to be switched are resistive, lamp, motor, capacitive, and inductive loads. There are two distinct types of loading associated with arcing. One type of loading produces current surges: these occur when a starting transient is greater than the steady operating current. Current surge types of load are lamp, motor, and capacitive loads. The second type of loading produces voltage surges; this occurs when the induced voltage is greater than the supply voltage, and is a characteristic of an inductive circuit. A motor, for example, may produce a current surge on start and a voltage surge on stop. A resistive load is subjected to neither a current surge nor a voltage surge because the transient is of the same order of magnitude as the steady state condition.

Circuits involving energy storage in capacitive or inductive form pose special switching and arcing problems. An arc may strike when the switch contacts first open, clear, then restrike upon discharge of stored energy. Repetitive restriking may occur as the switch contacts move apart.

Arcing during switching of electrical circuits causes problems in reliability because of deterioration of the switching device, and causes an additional problem by generating EMI. Suitable suppression of the arc may minimize these problems.

The usual DC interruption is caused by making an arc and forcing it into an unstable shape to create instability and eventual collapse. It is obvious that fast switching minimizes the duration of the arc, although typical inductive DC cir-

cuit arcs last longer than 5 milliseconds. Other elements in the circuit may radiate the interference that was conducted to them.

When AC is interrupted, the duration and magnitude of arcing depends upon the instantaneous voltages at the time of interruption. The interrupter should be designed so that the arc will not reignite after the voltage has passed a zero value. The transients produced upon closing an AC switch also depend upon the instantaneous voltage at the time.

Electrical circuits can be switched by several methods. Arcing is associated with switching by mechanical means such as manual switches, relays, circuit breakers, or thermostats. Arcing generates EMI with a frequency spectrum that extends into the ultra-violet band. Use of solid-state devices may eliminate the arc effect, but solid-state switches exhibit switching transients that may also cause EMI unless special transient-control measures are taken.

In designing equipments containing mechanical switching devices, care must be taken to maintain operational capability of contacts and at the same time suppress interference generated by switching. Often a gross approach to arc suppression is taken, some standard technique is applied, and a recommended component used without considering all aspects of the problem. The most direct solution, however, may lead to the generation of additional problems. Ramifications such as changes in circuit reliability, cost factor, weight, and system effectiveness must be considered. The system, in fact, may become overdesigned to a point where the generation of attendant problems abrogate basic design objectives. Some parameters such as cost factor become serious and intolerable in large systems. For this reason, recognition of the problems of arc suppression is especially important in such systems.

Suppression networks can be optimized by considering reliability, cost, physical size, weight, and other factors. Special networks can be designed for arc suppression. Such networks may accomplish this by delaying or eliminating any transients that occur during the switching operation. Arc suppression devices should be used as discussed for relay contacts in the subsection on relays. When the interrupted currents are large, the only effective means of limiting the interference might be to use short leads, to filter, and/or shield as much of the switching circuit as necessary.

The dielectric material used in switches must be chosen according to the intended use of the switch. High-frequency switches are usually made with ceramic material for insulation to avoid dielectric breakdown in the presence of arcing. Some switches are made with a sliding or wiping action that reduces arcing to a minimum, distributes contact wear, and reduces contact contamination. The wiping action introduces some interference by the variation of contact resistance for a short time after the contacts have initially touched or begun separating. A shorting switch has a "make before break" action that introduces only a small amount of interference because multiple changes in contact impedance do not occur. Mercury-type switches are excellent because they are quite contamination-free and exhibit little contact bounce, but their use is limited to stationary system applications. Vacuum switches, in which the contacts are enclosed in a vacuum envelope and operated by an external solenoid, are useful for

aircraft applications.

A high conductance contact occurs when simple contact under pressure wipes away film and tarnish, or light arcing causes rupturing of non-conductive oxides or sulfides. There are various types of contact alloys and platings; the type to be used should be determined by the application.

The thyratron-like latching characteristics of the thyristor make it ideal for eliminating interference due to contact opening. Reverse-blocking triode thyristors, commonly called silicon controlled rectifiers (SCR's), and bidirectional triode thyristors, usually referred to as triacs, are the most common types used in switching and power control.

An SCR can turn off only when the AC current through it naturally reaches zero in the process of reversing polarity, regardless of the load power factor. Because it requires no separate and sophisticated turn-off circuitry, the SCR does not interrupt current abruptly like mechanical contacts. Instead, it opens the circuit as soon as current reaches zero after gate drive has been removed. Circuit disturbances are minimum when current is interrupted at this instant. Turn-on logic can be developed from the opposite half-cycle. The turn-on gate control signal can be applied while the SCR is reverse-biased, but it will not begin to conduct until it begins to be forward-biased.

Because an SCR can conduct in only one direction, full-wave operation calls for two SCR's connected in reverse-parallel with gate control circuitry arranged accordingly. Alternatively a triac, which effectively functions like two SCR's in reverse parallel, can be used.

Thyristors are not entirely free of EMI effects, however. At turn-on time, a voltage spike is produced as forward bias voltage passes through the forward voltage breakover point. At turn-off time, stored carrier charges produce a current spike until a depletion region is established. Furthermore, a thyristor gate element is susceptible to EMI of high dv/dt. Capacitive charging currents can cause the gate to turn on the thyristor even though the magnitude of the gate voltage does not reach the rated triggering level.

Usual EMC problems involving switches are:

Interference Generation	Susceptibility
Switching transients	Voltage
Contact bounce	High-frequency signals
Arcing	Contamination
	Oxidation

CONNECTORS

Connectors can cause EMI by circuit geometric discontinuities when they can:

1. Create unshielded inductive loops and small capacitances that interfere with sensitive circuits

2. Constitute local circuits of inductance and capacitance with natural frequencies differing from those of other parts of the circuit
3. Constitute lumped impedance at certain points in the circuit which cause reflections and standing waves
4. Require consideration of the application, including the frequency range and insertion loss

Ideally, connectors should have:

Negligible resistance

Chemically inert surfaces

Resistance to gouging

Foolproof alignment to minimize contact damage

Adequate force between contacts

Little friction to minimize increase in resistance with use

Contamination-free design

Provisions for proper connections, including shielding

Proper dielectric properties

Moisture-proofing as required

Resistance to degradation due to age, wear, maintenance, and repair

Filter pins incorporated, if necessary

Compatibility regardless of varying intersystem contractors

There should always be a proper installation, including a good bond between the cable shield(s) and connector shell, as shown in Figure 15-19. Shields should be bonded all around the connector body periphery for optimum interference suppression. All connectors used as conducting paths for EMI should be bonded to the static ground. The maximum bonding resistance is considered to be 0.5 milliohm. Air gaps should be eliminated by woven mesh EMI gaskets or other means, if necessary. Other desirable features are protective coverings that extend over the male pins to reduce pin damage, the use of caps on unused connectors, the use of clamps to hold wires steady, contact materials designed for long life and proper pressure, and no loose or faulty contacts that might generate EMI.

Filter pins may be used where interference is in the VHF and UHF range. Most filter pins are not effective below 1 MHz. Use feed-through capacitors or filters mounted in a connector box where interference is below 1 MHz.

Usual EMC problems involving connectors are:

Interference Generation	Susceptibility
Improper contacts	Conductor problems
RF leakage	Radiation

Magnetic fields

Resonant frequencies

Characteristics

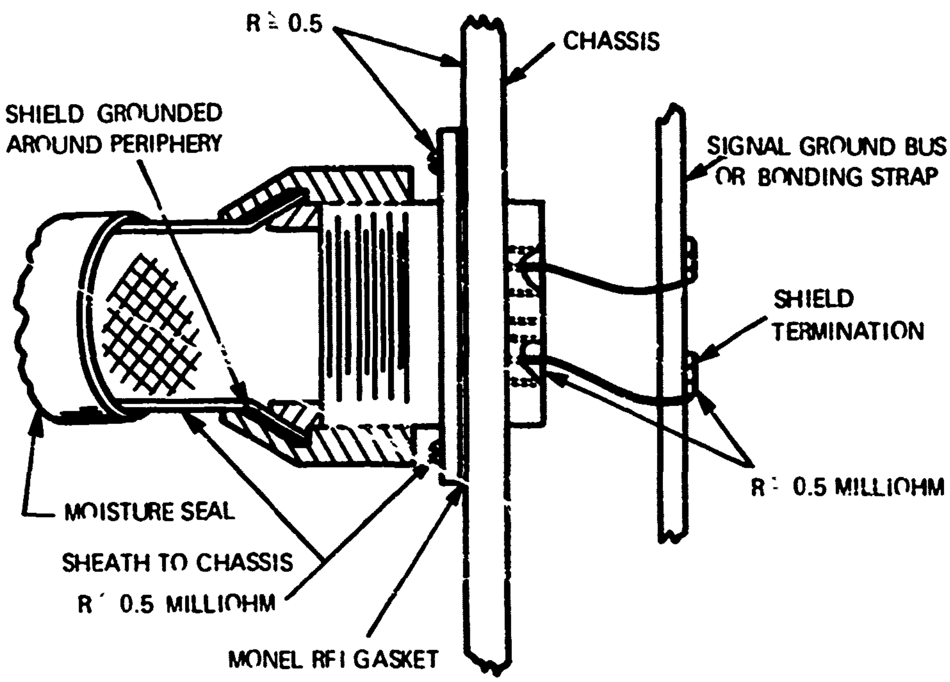


FIGURE 15-19 CONNECTOR GROUNDING

CHARACTERISTICS OF FUNCTIONAL CIRCUITS AND COMPONENTS

Previous sections have involved EMC problems of basic electronic circuitry parts. In actual practice, circuits have a combination of basic parts so that any part can affect similar or dissimilar parts. In the following sections, conduction, electrostatic, and radiation coupling theory will be covered, as well as EMC problems caused by miscellaneous phenomena.

CAUSES OF EMI

Magnetic Flux Linkage

Varying magnetic fields will be generated by alternating currents or transiently-changing currents and can cause an induced voltage that is proportional to the rate of change of ampere-turns, or d(IxN)/dt.

The interference voltage generated or induced into a circuit is proportional

to the flux linkages in that circuit so the area enclosed by the generating or susceptible circuit should be as small as possible. If a susceptible loop is near a long wire (effectively infinity), as in Figure 15-20, the loop induces the voltage, E,

$$E = 3.19 \times 10^{-8} fLI \ln \frac{r_2}{r_1} \tag{15-21}$$

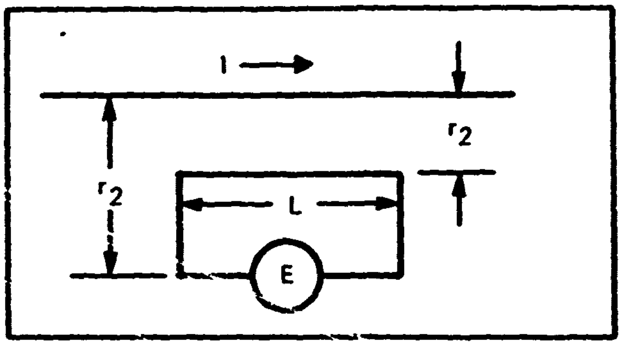


FIGURE 15-20 VOLTAGE INDUCED IN A LOOP

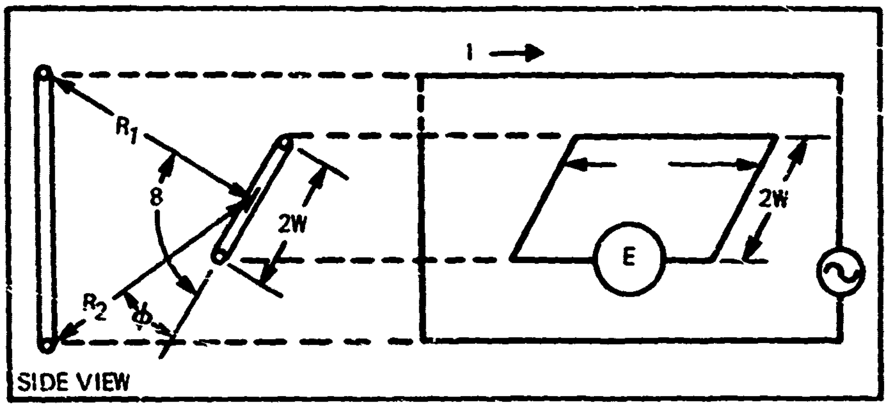


FIGURE 15-21 SUSCEPTIBLE LOOP AT AN ANGLE

where L is in inches and f is in Hertz. If the loop is at an angle to the interference source, as in Figure 15-21, the following equation applies:

$$E = 1.595 \times 10^{-8} fLI \left[\ln \left(\frac{R_1^2 + W^2 + 2R_1 W \cos\phi}{R_1^2 + W^2 - 2R_1 W \cos\phi} \right) - \ln \left(\frac{R_2^2 + W^2 + 2R_2 \cos\phi}{R_2^2 + W^2 - 2R_2 \cos\phi} \right) \right] \qquad (15\text{-}22)$$

From the preceding equation, it can be seen that the induced voltage increases proportionally with frequency, length of the closed loop, source current, and effective area enclosed by the pick-up loop. It can also be seen that, as the plane of the loop becomes perpendicular with the generating wire, the voltage becomes minimal.

The induced EMI voltage causes problems by driving current through the impedances of the pick-up loop and its connected loads. When the pick-up circuit impedance is low, the coupled voltage will be low; when the pick-up and interference circuit impedances are equal, the coupled voltage across the circuit will be one-half the induced voltage; as the load impedance is increased, the coupled voltage will approach the total induced voltage.

There are several ways of reducing the effects of magnetic coupling. Filtering can suppress interference, but because one source can couple into several susceptible circuits, it is better to filter the source rather than filter each of the susceptible circuits. As was stated, minimizing the frequency, the length of the pick-up loop, the interference current, and the area enclosed by the loop will minimize the induced voltage. The loop area can be made effectively small by running current-carrying conductors near their return or by twisting pairs of wires. Bypass capacitors should be of the feed-through type, and in any case, they should be mounted directly against the ground return.

Increasing the distance between interfering and susceptible components reduces the induced voltage exponentially. Other ways of minimizing coupling are by keeping the conductors perpendicular with each other and by shielding. The bases of shielding are:

1. Using high-permeability materials to confine the magnetic flux to the immediate vicinity of the interfering component
2. Using high-conductivity materials to reflect or short-circuit flux, thereby keeping it away from the susceptible component

Components must be kept away from an air gap in a magnetic circuit because of the great amount of leakage flux and because the usual shields on wiring give little protection against low-frequency magnetic coupling. The shielding effectiveness of high-conductivity material is a result of induced eddy currents that generate a counter-EMF flux. At low frequencies, a very thick layer of material is required.

Any current-carrying conductor generates a magnetic (H) field that causes a magnetic induction (B) field in the surrounding area. The H lines of force are concentric about the conductor and are closed loops. The "right-hand rule" states that if you grasp the conductor in the palm of your right hand with your thumb

pointing in the direction of conventional current flow (from the positive to the negative end of the conductor) the fingers will be pointing in the direction of the H lines of force. Current in a direction into the paper an illustration is printed on is shown as X, whereas current coming out is indicated by a dot or circle. These basic considerations are shown in Figure 15-22.

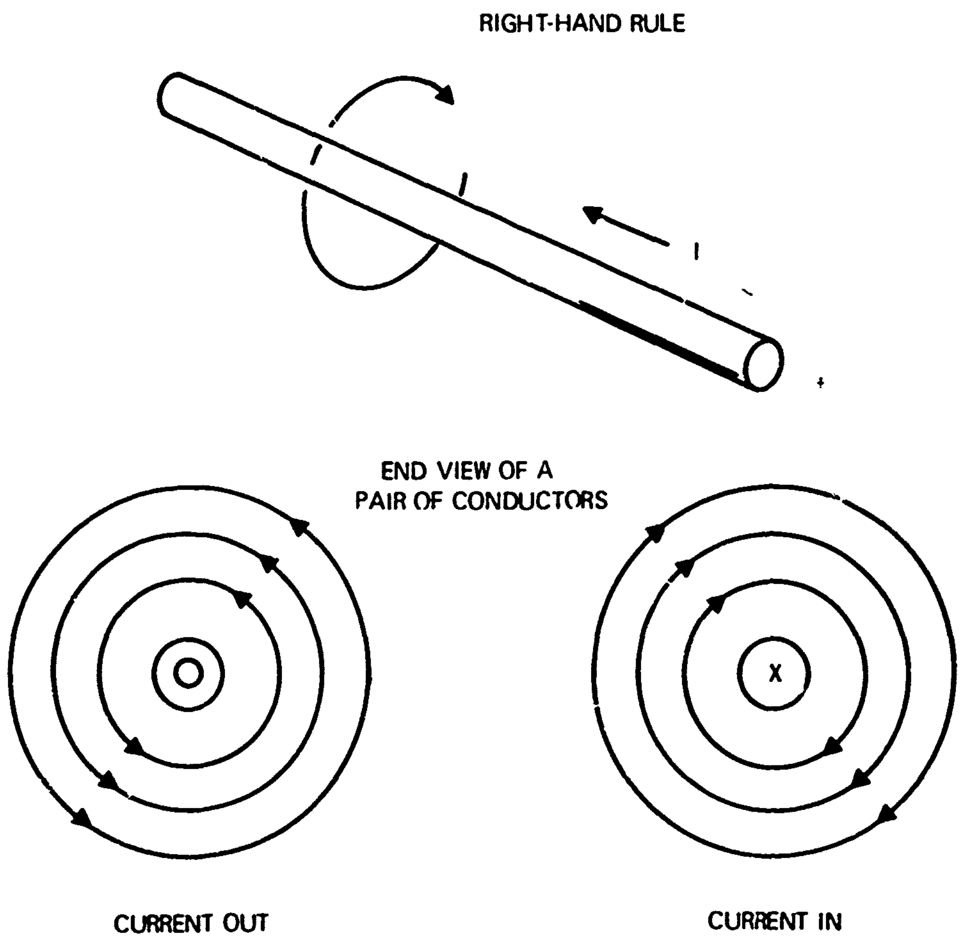


FIGURE 15-22 MAGNETIC FIELDS AROUND CONDUCTORS

A transmission line is shown in Figure 15-23, where two incremental lengths of the conductor, ΔS, are shown and the current flow (I) is as indicated. Assuming that point P is not between the conductors and is located in the plane defined by the two parallel and straight conductors, use of the right hand rule shows that the H force from each ΔS opposes the H force of the other. The resultant incremental magnetomotive force at point P is $\Delta H = \Delta H_2 - \Delta H_1$, where: (15-23)

$$\Delta H_1 = \frac{I_1 \sin \theta_1 \Delta S_1}{r_1^2} \tag{15-24}$$

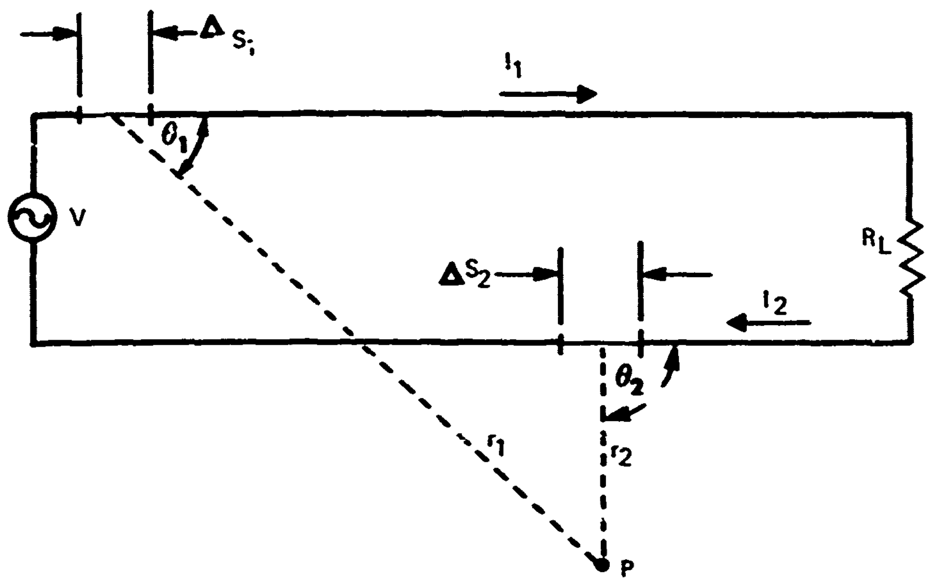


FIGURE 15-23 MAGNETIC FIELDS ABOUT TRANSMISSION LINES

and:

$$\Delta H_2 = \frac{I_2 \sin \theta_2 \Delta S_2}{r_2^2} \tag{15-25}$$

$$\text{Total } \Delta H = \Delta H_2 - \Delta H_1 = \frac{I_2 \sin \theta_2 \Delta S_2}{r_2^2} - \frac{I_1 \sin \theta_1 \Delta S_1}{r_1^2} \tag{15-26}$$

If

$I_2 = I_1 = K_1$. $\sin \theta_2 = \sin \theta_1 = \sin 90° = 1$.

$\Delta S_2 = \Delta S_1 = K_2$. and $K_1 K_2 = K$.

then:

$$\Delta H = \frac{K_1 K_2}{r_2^2} - \frac{K_1 K_2}{r_1^2} = \frac{K}{r_2^2} - \frac{K}{r_1^2} \tag{15-27}$$

which shows that the resultant force at point P is not O, but varies, depending upon r_1 and r_2. When the conductors are close together, with the above conditions, $r_1 \simeq r_2$. If we assume $r = r_1 = r_2$, so that:

$$\Delta H = \frac{K}{r^2} - \frac{K}{r^2} = 0 \qquad (15\text{-}28)$$

which means that if the ΔS's are very close together, there will be little H force ($\simeq 0$) at a point away from the conductors.

The preceding idea is used in transposition of telephone lines, and is shown in Figure 15-24. This method allows hundreds of telephone circuit lines to be side-by-side without shielding, and it is obvious that protection from interference increases wtih the number of twists per unit length.

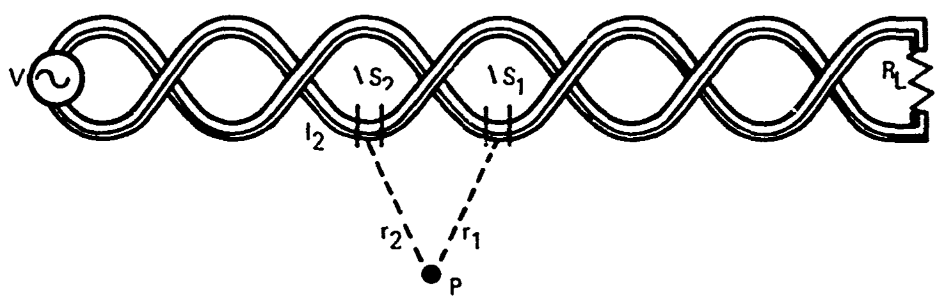


FIGURE 15-24 MAGNETIC FIELDS
FROM A TWISTED PAIR OF CONDUCTORS (TRANSPOSITION)

Figure 15-25 shows an end view of conductors of a circuit which are encased in a high-permeability magnetic material tube. The magnetomotive forces H_1 and H_2 induce magnetic flux B_1 and B_2, respectively. B_1 and B_2 are opposite and, if equal, the net flux around the pipe is zero. If there is a small imbalance in B_1 and B_2, the resultant flux has a low reluctance path through the iron pipe, which acts like a magnetic short circuit to keep the magnetic field from passing through. However, if saturation of the magnetic material is caused by the magnetic fields of the internal or external conductors, the permeability of the material decreases toward unity and its magnetic shielding properties are reduced, probably allowing magnetic field radiation.

A circuit can be enclosed in a high-conductivity metal enclosure. Figure 15-26 shows a cutaway portion of a copper ring, usually called a shading ring, enclosing a coil. When the coil's alternating magnetic field cuts the shading ring, the induced voltage in the small resistance causes a large current flow in the ring, setting up an alternating field that opposes the coil's magnetic field. The magnetic field outside of the ring is thereby reduced. As the resistance is minimized,

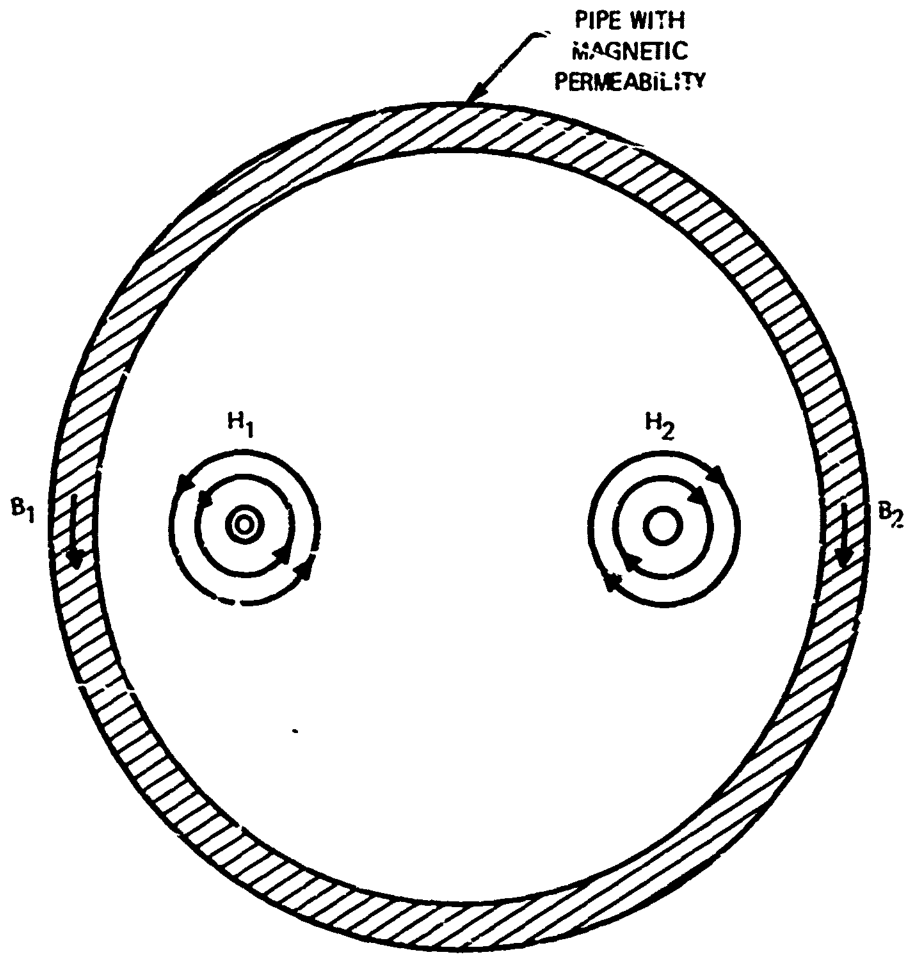


FIGURE 15-25 SHIELDED TRANSMISSION LINE

the field is decreased. This arrangement can be thought of as a transformer, as:

Shading Ring Concept	Transformer
Coil	Primary winding
Space around coil and ring	Core
Shading ring	Secondary winding
Magnetic field between coil and ring	Leakage reactance field

The shading ring has no effect on DC magnetic fields when the fields are not varied. If a conductive box is used, the sides act as a shading ring, with the top and bottom effectively an infinite number of concentric shading rings.

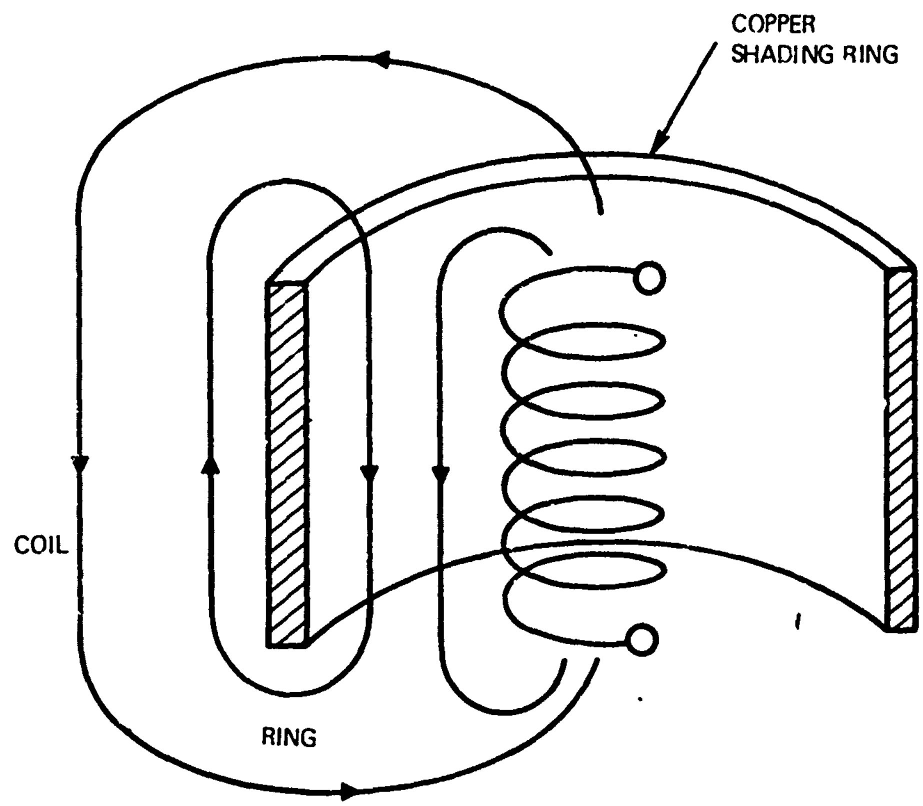


FIGURE 15-26 COIL SHIELDED BY A COPPER SHADING RING

Figure 15-27 shows the use of a shading ring in a transformer or choke. Television receiver power transformers usually have shading rings to help prevent electron beam deflection by the transformer's magnetic field. Chokes are potentially one of the worst interference sources due to the large harmonic content of power supply current, the rectifier switching transients, and the magnetic-circuit gaps that prevent DC saturation. In the case of this type of choke, the shading ring in Figure 15-27 must be extended so it covers the gap. The unsymmetric structure of the fields would also require the choke to be enclosed in a high-permeability material box of sufficient thickness and distance from the choke to prevent saturation.

Figure 15-28 shows how a semi-toroidal choke or transformer is made, minimizing the weight and size. The coils act as shading rings as they are placed over a core gap. When the choke is enclosed in a magnetic material box, external fields can be reduced by approximately 45 dB over a conventional E-lamination transformer.

A toroidal coil, as in Figure 15-29, has the least external field of any inductor, whether the core is of non-conductive nonmagnetic or magnetic material. These coils can be stacked one above another with very little magnetic coupling.

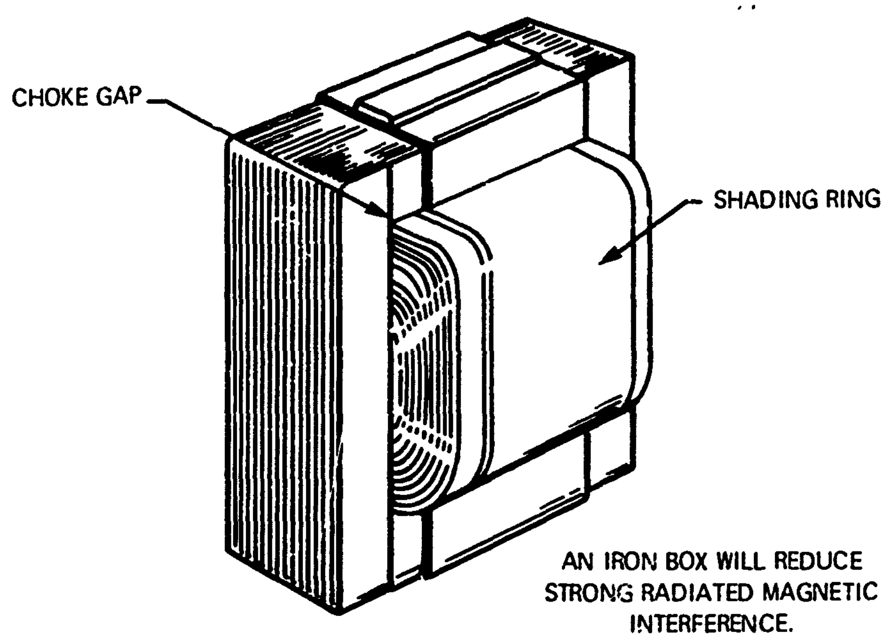


FIGURE 15-27 SHADING RING IN A TRANSFORMER OR CHOKE

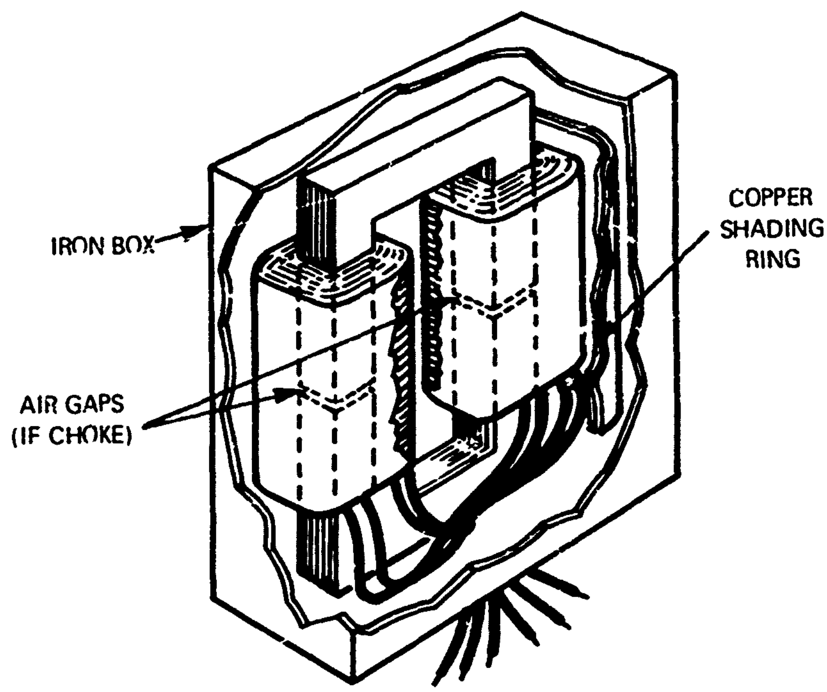


FIGURE 15-28 MAGNETICALLY-SHIELDED TRANSFORMER OR CHOKE OF SEMI-TOROIDAL CONSTRUCTION

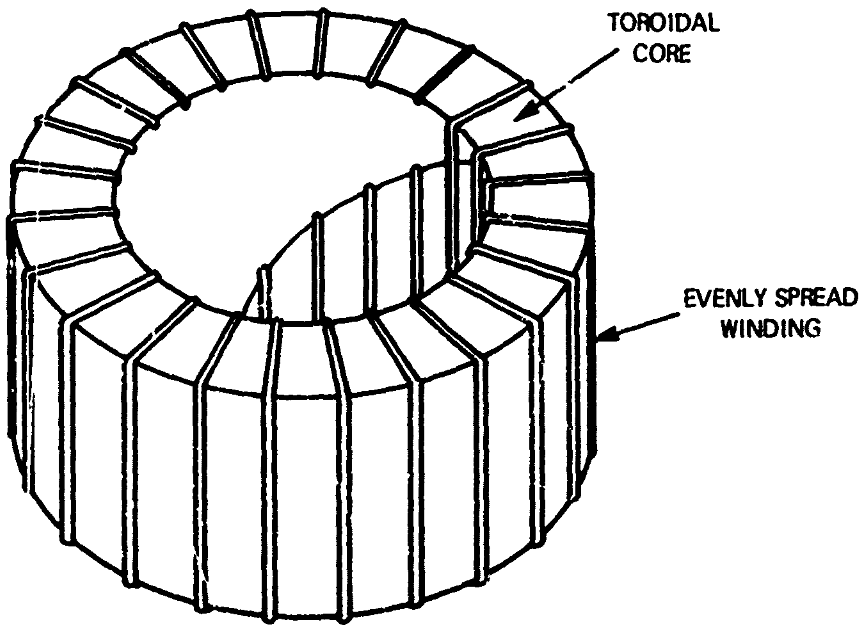


FIGURE 15-29 TOROIDAL CORE COIL

Telephone loading coils are made in this way with hundreds of coils in the same enclosure. With the use of high-frequency core materials, this construction is used up to frequencies in the hundreds of megahertz.

Techniques for reducing the susceptibility to magnetic fields are essentially the same, but it is usually more economical to minimize interference at the source rather than at each susceptible component of the circuit.

When the magnetic field has an unchanging or approximately unchanging intensity, it can cause interference in devices that are responsive to a DC magnetic field. Some examples of this are magnetic compasses, Hall-effect devices, cathode-ray tubes, tape recorders, memory cores, and superconductors. Small RF or AF reactors and transformers with open ferrite or powder slug cores are examples of components that are usually used with AC fields but whose characteristics are changed because of magnetic core saturation by a DC field. Semiconductors are somewhat susceptible to AC and DC magnetic fields; the degradation can be determined from the Hall coefficient, conductivity or carrier density, and dimensions.

Laser devices can be modulated by moderately strong magnetic fields, and future devices, particularly high-precision devices, may be susceptible to magnetic fields. It has been found that cold-rolled steel cabinets and supports that have been handled by magnets may exhibit permanent magnetism. This magnetism may directly affect nearby components or provide a polarized shielding from external fields by having the steel saturate at a lower value for one polarity of flux than for another.

Electrostatic Coupling

Electrostatic coupling occurs when an electric field developed by one circuit exerts an influence on another circuit through a dielectric medium between them. In Figure 15-30, C_C is the undesired coupling capacitance between the two circuits. C_{G1} and C_{G2} are the distributed capacitances to ground of circuits 1 and 2, respectively. Minimum electrostatic coupling occurs when the impedance to ground of the second circuit is low compared to the impedance of C_C. Therefore, minimum interference will occur with the susceptible-circuit-to-ground capacitance as large as possible near the interference source, a limit being the required high-frequency response. The usual methods of reducing coupling are by keeping the circuit conductors physically close to the ground plane (with respect to frequency response) and keeping conductors of one circuit as far away from the other circuit conductors as possible.

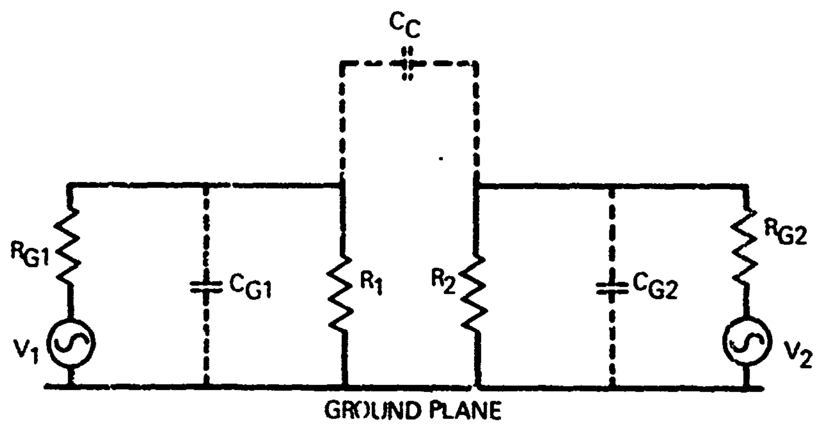


FIGURE 15-30 ELECTROSTATIC COUPLING

If the coupling is still too great, an electrostatic or Faraday shield can be placed between the two circuits. As shown in Figure 15-31, the shield is an extension of the ground plane and is a termination for the electrostatic lines of force. Electrostatic shield should be large sheets of high-conductivity metal bonded directly to the ground plane or connected to the ground plane by one or more large diameter and short conductors. Any appreciable self-inductance of the shield or its ground return will raise its potential above ground and impair its effectiveness.

Figure 15-32 shows a transmission line between a source V_1 and its load R_L. Interference source V_2 is electrostatically coupled to the line through stray capacitances C_1 and C_2. Transmission line capacitances-to-ground are C_3 and C_4. The top sketch can be redrawn in the form of the bridge circuit in the bottom sketch. C_1 and C_3 form a voltage divider to ground for V_2, as do C_2 and C_4. If the EMI voltage at point A is the same as that at point B due to the voltage di-

viders, no interference current will flow through R_L. If this is true, R_L is capacitively balanced with respect to interference source V_2. An unbalance will cause current flow through R_L. This can be prevented by using variable capacitors in shunt with the capacitances.

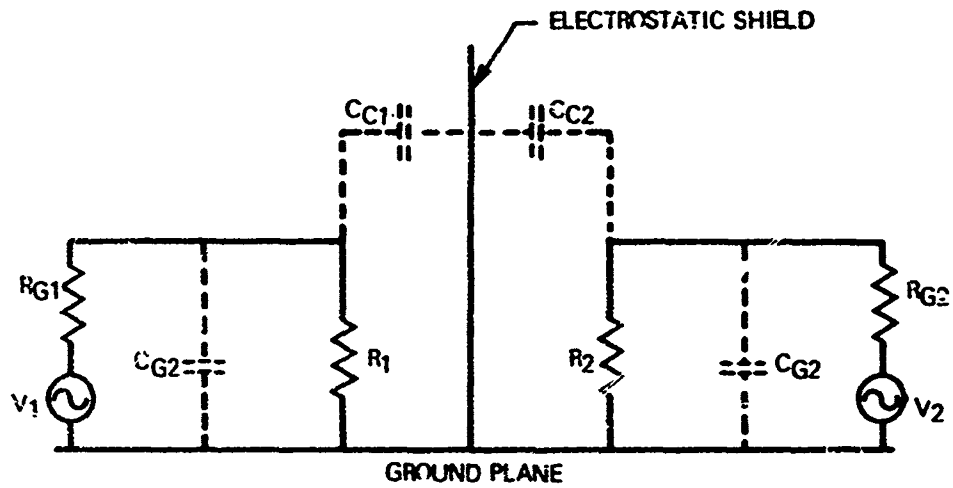


FIGURE 15-31 ELECTROSTATIC SHIELDING FIGURE 15-31 ELECTROSTATIC SHIELDING

Figure 15-33 shows the effective circuits when a transmission line is twisted. In contrast to the last example, transposing the conductors results in balancing the stray capacitances, as well as the conductor-to-ground capacitances, so the bridge is balanced.

Figure 15-34 shows a twisted-pair transmission line enclosed in an electrostatic shield. The twist cancels the magnetic field and the shield is grounded at one end to eliminate low frequency interference. Interference source V_2 is effectively connected to the other end of the shield, causing a current along the shield to ground. The resistance of the shield develops voltage drop, which is capacitively coupled to the transmission line. The capacitance from each transmission line conductor to the shield is the same, and if the distributed capacitances from each conductor to ground at V_1 and R_L are the same, the circuit will be capacitively balanced with respect to interfering electrostatic sources. A balanced transmission line or circuit exhibits less susceptibility as well as less propagation of electrostatic interference.

At high frequencies, multiple-point grounding of shields is used to minimize standing waves. High frequencies can also necessitate the use of multiple shields, with the objective of eliminating RF currents on the external shield surface nearest to the susceptible components.

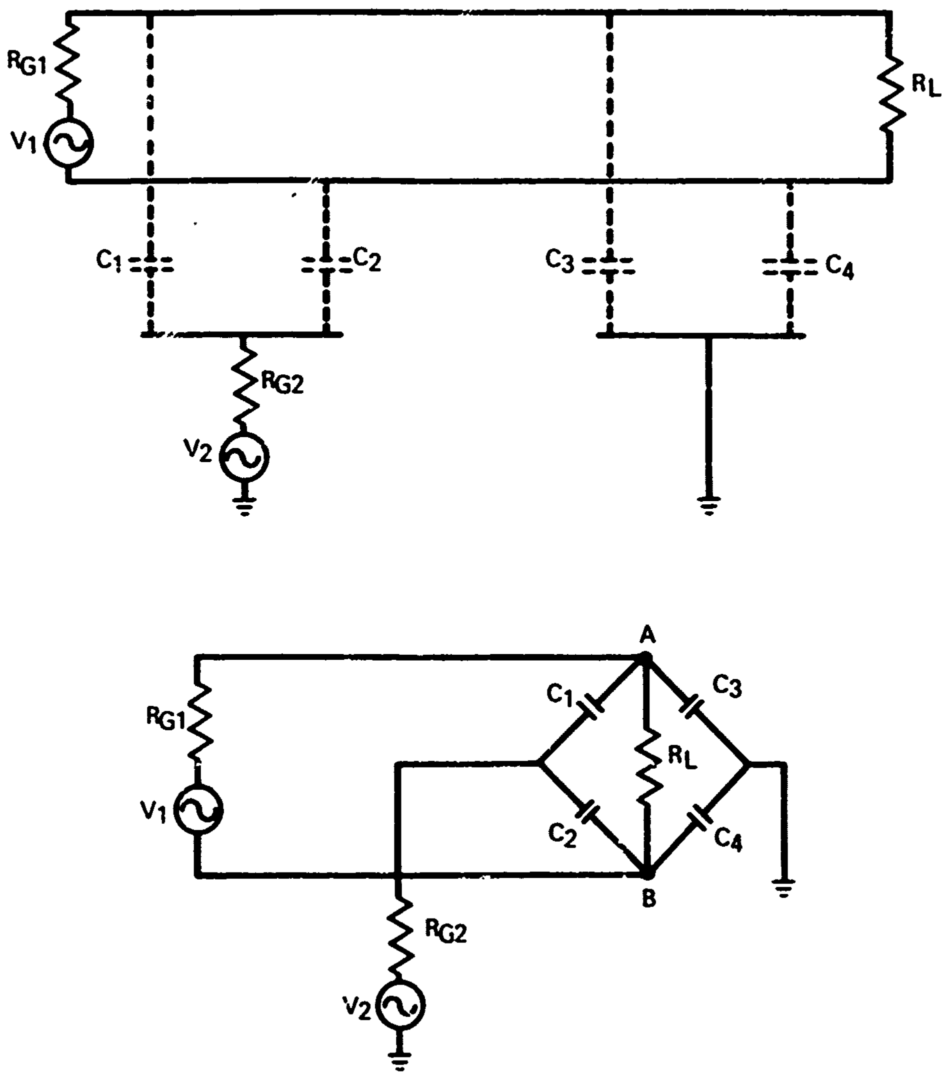


FIGURE 15-32 ELECTROSTATIC COUPLING EFFECTS IN A TRANSMISSION LINE

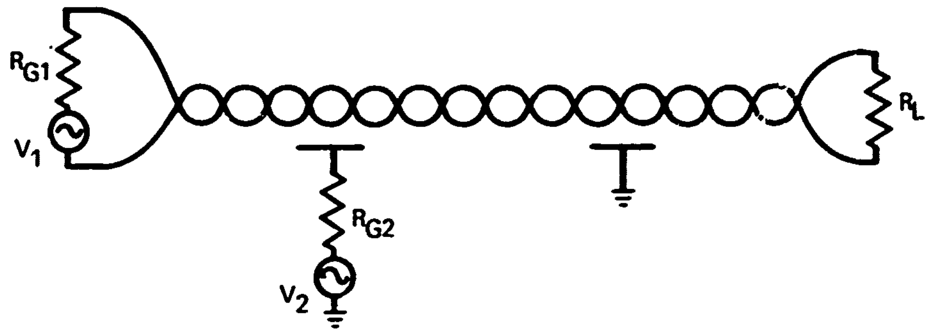


FIGURE 15-33 TWISTED-PAIR TRANSMISSION LINE ELECTROSTATIC COUPLING

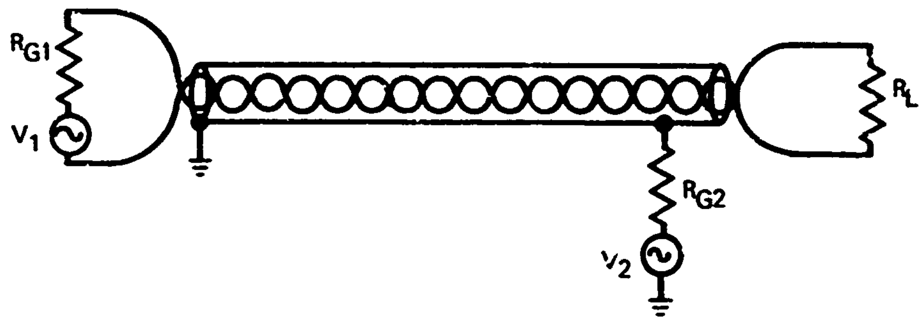


FIGURE 15-34 SHIELDED TWISTED-PAIR TRANSMISSION LINE ELECTROSTATIC COUPLING

Conduction and Common-Impedance Coupling

Common-impedance coupling in an unbalanced transmission line will be treated using Figure 15-35 as an example. In the top sketch in the figure, source V_1 with its internal resistance R_{G1} and load R_{L1} and source V_2 with its corresponding R_{G2} and R_{L2}, are all connected to a common line (bus) having an impedance shown as a long resistor. The part of the impedance common to both circuits is shown as R_C. A current in either circuit will cause a voltage drop across R_C that appears as a series source in the other circuit. The objective of EMI control is to reduce to a minimum the common impedance shared by the two circuits. The bottom sketch in Figure 15-35 is an example of conductive coupling in which the common bus is the outer conductor of coaxial lines and R_C again represents the common impedance. Balanced lines usually require well-balanced transformers at both the source and load, so, for economy and space considerations, unbalanced lines are used, and the selection of connection points is very important.

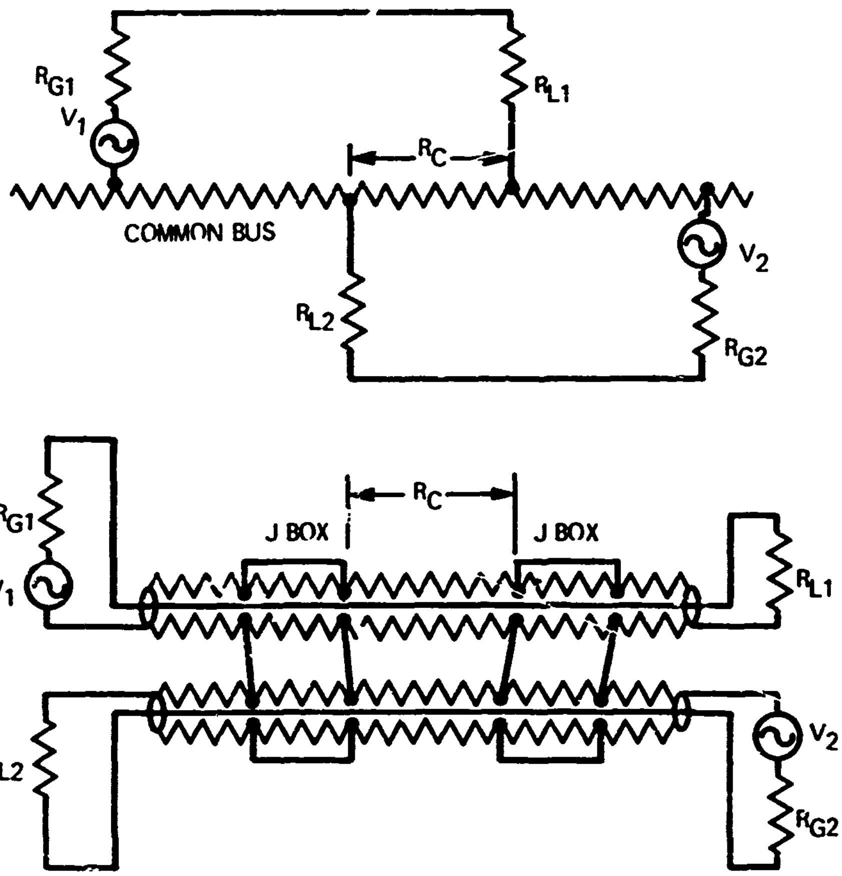
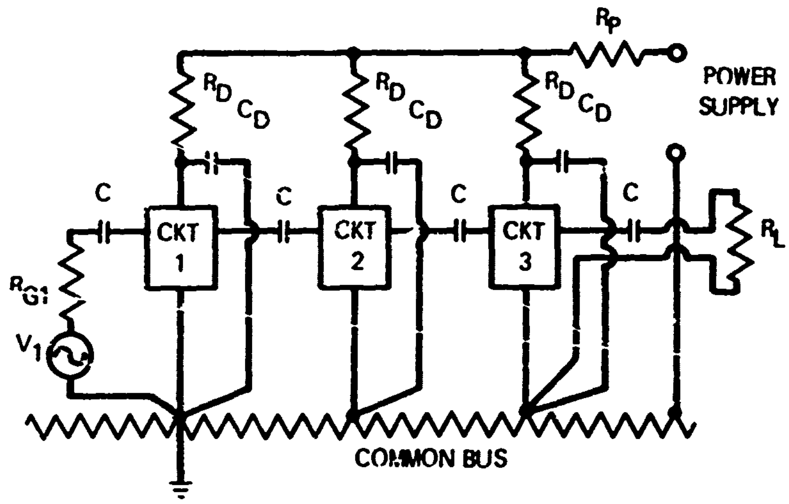


FIGURE 15-35 CONDUCTIVE COUPLING THROUGH GROUND

Electronic equipments usually consist of chains of circuits interconnected to perform an overall equipment function. The top circuit in Figure 15-36 shows a simple chain of three circuits powered by a common power supply. V_1 with its internal impedance R_{G1} is the signal source and the capacitors C couple the signal from circuit to circuit. R_D and C_D are power supply decoupling networks. C_D provides a low impedance to the common or ground bus for circuit-generated signal components appearing on the circuit's power supply lead. R_D provides an impedance to reduce the flow of signal currents through the power supply internal impedance R_P. If the power supply decoupling networks were not present, R_P would be a common-impedance coupling network at signal frequencies for the three circuits. It would therefore act as a signal feedback path from the output circuit to the preceding circuits. If the signal gain in the loop formed by the normal signal path and the feedback path approaches unity, the circuit chain will have very bad transient characteristics, and operation will be generally unreliable. If the gain in this loop exceeds unity, the circuit chain enclosed by the loop will

oscillate, thus destroying its normal function.

The bottom circuit in Figure 15-36 shows an alternative power supply decoupling arrangement. The advantage is greater signal attenuation between the output and input circuits for the same number of decoupling components. If the impedances R_D consist of resistors rather than inductors, this arrangement may have the disadvantage of unsatisfactory supply voltage for the first circuit. A combination of both decoupling methods is used.



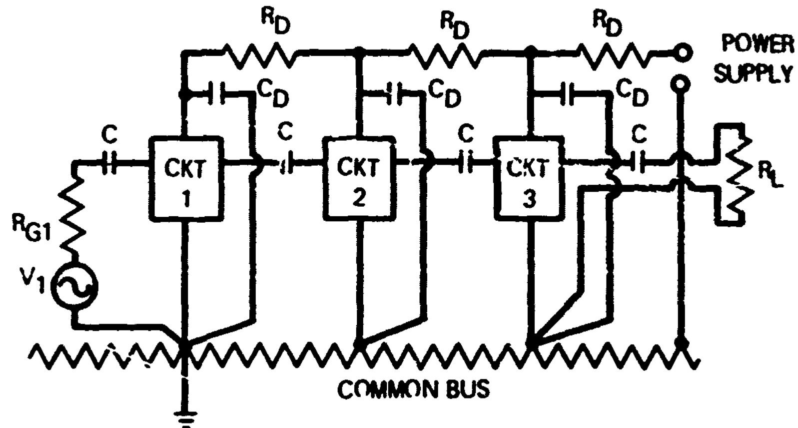


FIGURE 15-36 CONDUCTIVE COUPLING DUE TO POWER ARRANGEMENT

To minimize conductive coupling through the common impedance of a ground return, a bus structure called a ground tree is used as shown in Figure 15-37. The trunk of the ground tree is a very low-impedance conductor running through the equipment to which the branch ground bus of functional circuit groups is connected. Branch connections to the trunk are made to minimize undesired conductive coupling between circuit groups, whereas each ground twig on

a ground branch is the ground bus of a circuit chain.

If conductive or electrostatic coupling ground loops are not negligible, they are usually removed by changes to the ground tree or opened by coupling transformers, balanced transmission lines, or separate power supplies.

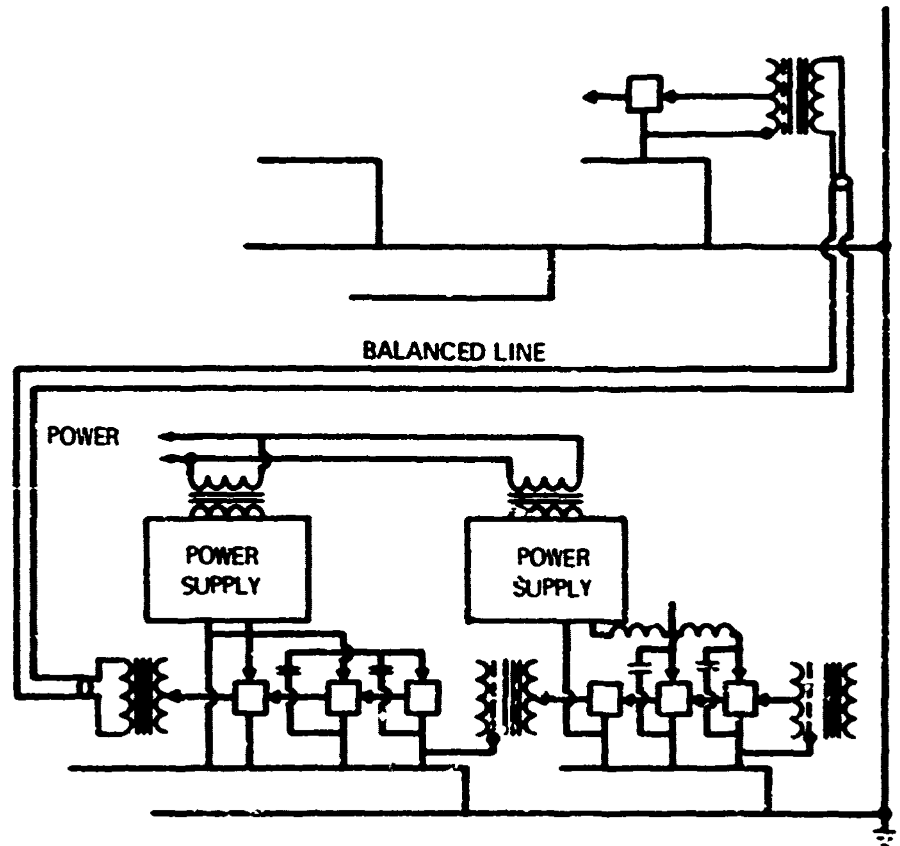


FIGURE 15-37 A GROUND TREE

Radiation Effects

Radiation is the process in which energy is released from a body in the form of electromagnetic waves that have vibrations transverse to the direction of propagation. This includes the radiant energy associated with the electromagnetic spectrum from the highest energies (shortest wavelengths) of secondary cosmic rays, the gamma rays from radioactive disintegrations of atomic nuclei, X-rays, ultraviolet rays, visible light, infrared, solar radiation, radio, and very long electric waves. All of the preceding have the wave properties of refraction, reflection, and polarization. In many other phenomena, these radiations act as corpuscular quanta, or chargeless and massless photons, thus indicating a second nature, which can be only depicted mathematically by wave-mechanics equations.

In modern terms, "radiation" also includes particles which possess mass and which might be electrically charged. Beams of such particles may be considered "rays" that have the dual nature mentioned above. Two effects produced by irradiation are the transient effect from ionization of the material and the permanent effect caused by changes in energy character of an atomic structure and atomic displacements. Many electronic parts are affected by this type of radiation, but semiconductors tend to be most vulnerable because of their regular crystal structure and purity.

As an example, the "gamma effect" is a transient phenomenon causing photocurrents that are multiplied by the gain of the transistor elements in a circuit of an integrated circuit (IC) component. An IC designed against the gamma effect is called a "hardened" device and uses NiCr resistors over oxide rather than the diffused resistors common to junction-isolated circuits. Dielectric isolation eliminates the photocurrent flow between the collector and substrate.

Another type of radiation, neutron bombardment, causes permanent damage by disturbing the lattice structure of the crystals, causing a degradation of current gain to the active elements. Corrective steps include small geometry designs, shallow diffusions, selective gold doping, and the use of minimum bulk materials.

In its usual connotation, radiation from an element acting as an antenna is composed of three fields: an inductive electrostatic component with a field strength proportional to $1/r^3$, an inductive magnetic component changing as $1/r^2$, and the radiation field which varies as $1/r$. Electrostatic and magnetic fields have greater strength than the radiation field up to a point about $\lambda/2\pi$ from radiating element where the radiation field is equal to the induction field. The radiation field can cause undesired response, signal distortion, or desensitization of varying degrees, depending upon the components acted upon and the strength involved. Radiation can cause nonlinear circuits to produce undesired harmonic frequencies, overheating of components, erroneous triggering, and many other effects that might be difficult to predict.

Nonlinear Circuits

Some electronic circuits are intentionally designed to operate into their nonlinear regions to accomplish a circuit function, and some circuits may unintentionally be caused to operate in a nonlinear fashion due to overload, overdrive, nonlinear loading, or other circuit conditions including the intrusion of EMI. Devices such as electron tubes, semiconductors, and saturable reactors can behave in a nonlinear fashion over some portion of their operating range. When circuit nonlinearities are presented to signal current flow, the waveform distortion results in generation of harmonics, intermodulation products, and switching noise which may be radiated or conducted from the circuit.

Because the principles involved in oscillation and modulation depend upon the transfer characteristics of a nonlinear device, there is a great potential for generating spurious and harmonic outputs.

For an oscillator, nonlinearity is needed to limit the amplitude of oscilla-

tion. Amplitude limiting can be provided by the transfer characteristic of the amplifier used in the oscillator, by diode limiters, by saturable reactors, or other circuit elements. Purity of the generated waveform is dependent upon the degree of amplitude limiting. Low efficiency (20-30%) Class A oscillators give the best spectral purity, while high efficiency (65-85%) Class C oscillators give the poorest because the active element delivers its output in pulse form. When an oscillator is keyed on and off abruptly or made to change frequency abruptly as in telegraphic or pulse service, keying transients are generated that contribute to degradation of waveform purity. Circuits such as square-wave oscillators used in DC-to-DC converters, and sawtooth oscillators used in CRT and swept-frequency devices generate waveforms rich in harmonics. Harmonic content generally increases with oscillation amplitude and circuit loading.

For communication systems, the oscillator of choice is usually crystal controlled or crystal stabilized to provide the requisite frequency stability. When an oscillator is used as a part of a transmitter, its noise and harmonic frequencies may be amplified to appreciable proportions and emitted from the antenna, cabinet, or connecting cables unless precautions are taken. When an oscillator is used as a part of a receiver, its noise contribution to mixer action can degrade the receiver noise figure, and its harmonic frequencies can cause the receiver to fall victim to spurious responses. An RF oscillator should be lightly loaded and followed by buffer stages to isolate and filter.

Buffering isolation is especially important to equipments using semiconductors. The inherently poor isolation between input and output of a transistor, a consequence of the transistor's internal impedance, may allow nonlinear circuit loading effects in the buffer and beyond to be reflected back to the oscillator to affect its purity of waveform. Nonlinear effects such as sharp changes of driving current in some stage caused by a tube grid or transistor input drawing current over one portion of a cycle and not another, can affect more than just one stage. Designers using transistors should be familiar with characteristics of transistor reverse transfer (y_{rb} admittance parameter) and its effect upon linearity in cascaded circuits.

Circuits in which changes in output loading are reflected back to the input circuit to influence input admittance are not limited to transistor circuits. Grounded grid circuits using vacuum tubes exhibit a similar effect as a result of commonality of input currents and output currents in the driven cathode circuit.

The inherent nonlinearities of mixing and modulation processes can contribute to the generation of undesired spectral components that may be radiated at significant power levels unless sufficient filtering or shielding is provided. Basic amplitude modulation consists of applying the desired band of audio or video modulating frequencies (f_m) to a mixer or modulator stage that is being driven at a suitable carrier frequency f_c. The modulated stage, which must be nonlinear, produces at its output a complex wave that contains a series of mixer products as follows: first order products f_c and f_m; second order products $2f_c$, $2f_m$, $f_c + f_m$, $f_c - f_m$; third order products $3f_c$, $3f_m$, $2f_c + f_m$, $2f_c - f_m$, $f_c + 2f_m$ and $f_c - 2f_m$; and so on. Most of the mixer products intrinsic to the modulation process are unwanted and must be attenuated by appropriate filtering to keep

them from becoming sources of EMI.

For conventional double-sideband-full-carrier A2 or A3 emission, the carrier f_c, along with the two principal sidebands $f_c + f_m$ and $f_c - f_m$, is passed by subsequent tuned bandpass filters. This type of emission is usually developed in a high level modulator, which is often followed only by a plate tank circuit and possibly an antenna tuner. Thus the unwanted mixer products are not only at a high level, but the mixer (modulated stage) is likely to be followed by a minimum of filtering.

Suppressed carrier modulators normally use a balanced mixer that attenuates the carrier and its odd-order harmonics to a degree dependent upon the accuracy of the balance. For single sideband, the mixer is followed by a bandpass filter of high selectivity that offers attenuation on the order of 60 dB to all but the wanted sideband. To achieve this order of attenuation, the single sideband filter must be designed at a fixed frequency and f_c chosen accordingly. To reach the desired operating frequency f_o, one or more additional modulators must be used to heterodyne the modulated RF against a selectable-channel oscillator to reach the transmitter output frequency f_o. Each of the additional modulators produces a series of mixer products of the same order as indicated for the first one, and these products must be removed by filtering. Normally, each of the modulators is followed by a selective buffer amplifier tuned to amplify the desired mixer product and attenuate the rest. The designer must make a wise choice of frequencies to avoid having an unwanted mixer product fall within the passband of one of the tuned amplifiers.

Ideally, a basic amplitude modulated signal should not cause distortion of an allowed emission bandwidth when original modulation frequency components are translated faithfully up to an output frequency. However, overmodulation in a modulated stage, or nonlinearity in any stage that amplifies amplitude-modulated signals, will produce sideband splatter that causes transmitter output to occupy more than the authorized amount of baseband spectrum.

High level modulation permits use of efficient nonlinear Class C amplifiers for intermediate RF exciter stages, even though they generate harmonics. In fact, frequency multiplication requires the exciter stages to generate and amplify harmonics of a master oscillator frequency. The high-level modulated stage, which is also a power amplifier, is nonlinear by necessity and therefore a generator of harmonics. Thus, even without modulation present, consideration must be given to suppressing the harmonic contributions of each RF stage.

The problem of maintaining spectral fidelity past a modulated stage is somewhat different in the case of low-level amplitude modulation, which includes but is not limited to single sideband with suppressed carrier (A3J) or pilot carrier (A3A), or double sideband also with suppressed carrier or a pilot carrier (A3B). Because single sideband and independent sideband modulation must be implemented with filtering networks, modulation is commonly performed at low power level to simplify the design of filter elements. Because of low level modulation and subsequent filtering used to establish a desired modulation format, subsequent buffer and power amplification stages will have to be completely distortion-free. In practice, this requirement is difficult to meet. The cumulative

distortion characteristics of cascaded amplification stages can result in appreciable distortion power even though each stage is designed to be reasonably linear. It is difficult to design a linear AM power amplifier than can drive a radiating antenna as a load with reasonable efficiency without introducing distortion. Distortion is primarily evident as sideband splatter.

The harmonic output of a transmitter using low-level modulation is likely to be much less than that of its high-level counterpart when usual operating precautions are observed. This is because the degree of nonlinearity in the power amplifier stages is less, and a larger number of tuned circuits is interposed between the modulator and the output. The troublesome areas to be avoided are those frequency ranges in which unwanted mixer products fall near or in the passband of the tuned circuits.

In angle modulation, however, and particularly in frequency modulation (phase modulation is almost identical), the modulation process is essentially nonlinear, and the resultant sideband components are distributed over a very wide range of frequencies (theoretically infinite in extent), the distribution of which can be determined by the usual Bessel function expansion method. For example, sine wave frequency modulation of an RF carrier by a 1 kHz tone (f2), results in a distribution of sidebands about the RF carrier frequency at harmonics of the 1 kHz modulating frequency. In practice, harmonic sideband components that are spectrally located beyond (2 + 2B) times the modulating baseband, where B is the index of modulation and is defined by

$$B = \frac{\Delta\omega}{\omega m} \tag{15-29}$$

are considered to be of negligible importance insofar as their contribution to the intelligibility of the corresponding received FM signal is concerned. However, these negligible components may still only be 60 dB or less down from the unmodulated carrier power. The larger the value of B used, the greater the spread of the spectral components, for the same modulating signal waveform. For FM transmitters operating at power levels of about a megawatt, interference due to sideband spread containing components of about a watt can become quite significant.

One of the advantages of frequency modulation is that the baseband intelligence is contained only in the instantaneous frequency variations of the FM signal. Therefore, nonlinear processes may be used to limit noise-rejection amplitude in both the transmitter and receiver without appreciably disturbing the intelligence content of the signal. For a transmitter, this means that incidental amplitude distortion in power amplification stages does not detract from signal intelligibility. However, in terms of EMI, any distortion of the transmitted FM signal causes additional sideband splatter and resulting interference with cochannel services. Therefore, amplitude modulation in its various forms is in principle capable of providing good spectral purity because of the nature of the modulation involved. Angle modulation, through its inherent nonlinearity, even in the ideal case, causes the equivalent of sideband splatter or distribution of sideband energy representing harmonics of the modulating signal translated about

the RF carrier, plus intermodulation products between baseband spectral components.

In angle modulation, the carrier is usually present to some degree. However, under modulation conditions, the carrier component is reduced as modulation index β is increased, since the total transmitted power remains invariant regardless of the amount of modulation. Under certain modulation conditions, the carrier may actually disappear and the sidebands contain the total transmitted power.

The essential non-linearities of the modulation process can serve as mechanizing functions for the generation of undesired output frequencies. For amplitude modulation, the prime cause is the inability to provide ideal linear modulating elements and the limitations of post-modulation tuned circuits in suppressing undesired spurious and harmonic outputs resulting from modulation. In angle modulation (even with the use of ideal elements), the fundamental non-linearity of the modulating process results in generation of desired spurious and harmonic products which again cannot be entirely eliminated by post-modulation filtering. In both cases, the frequencies at which these undesired signals appear can generally be predicted analytically. However, their importance in generating RFI is relatively unpredictable since in many instances uncontrolled or unknown equipment design and use factors are involved.

RF transmitters typically consist of separate oscillator, modulator, and power amplifier sections. Separation of function is desirable since the signal generation/processing assigned to each section can be accomplished more efficiently. Modulation of an oscillator, for example, is undesirable for transmission purposes because both AM and FM of the carrier will result, even though the modulation is designed to produce only one or the other. Therefore, modulated oscillators are rarely used, with the notable exception of pulsed power oscillators in microwave radar and beacons.

The types of EMI attributable to the power stages of the RF transmitter are 1. incidental FM/AM when the power stage is a modulated oscillator, 2. sideband splatter due to nonlinearities or overmodulation when the power stage is also the high-level modulated stage. 3. amplification of harmonics and spurious mixer frequencies from frequency multipliers, frequency synthesizers, and 4. generation of harmonics and intermodulation products due to nonlinearity.

Splatter from nonlinearities in the RF amplification/modulation process is essentially an undesirable spectral spreading beyond the normal bandwidth occupancy. Undesired distortion products may also appear within the normal signal band, but this cannot be regarded as EMI.

Other (Chemical, Temperature, Pressure, Friction, Light)

Some EMC problems are caused by any of a number of possible causes. An example is in the commutation of DC motors and generators. Arcing is caused each time the current is interrupted at the trailing edge of the brush as the commutator passes under it. Arcing also occurs because of the lack of constant uniform pressure at the conduction area, which can be caused by eccentricities, contact area oxidation, or improper spring pressures.

Other EMC problem mechanisms are:

1. Chemical. Primarily, this type of problem exists due to chemically different materials being used in contact with each other intentionally, as a conductor to a connector, or unintentionally, as contamination on one of the mating surfaces. It can cause generation of voltages, affect the structure of components due to the passage of current, or even cause varying contact resistance and eventual electrolytic decomposition. Problems caused by ionic contact potential usually do not occur if AC is used, because the polarity effects are continually bidirectional and cancel each other. Contact materials must be properly selected for qualities commensurate with their use.

2. Temperature. All components have a temperature characteristic which must be considered for proper design. Temperature changes can cause thermoelectric voltage generation, and changes in resistor, capacitor, and semiconductor impedance and noise values. Temperature can also change the temper of relay and switch springs and thereby cause a varying contact resistance by change of pressure and conductivity. Expansion caused by overheating can cause varying contact resistance between metals that are intended to have a low contact resistance. High-resistance joints can cause reduction in circuit current, high voltage across the joint, eventual overheating, and melting at the joint.

The change of characteristics can have temporary, cumulative, or permanent consequences, and can result in many types of malfunctions. Common reasons for temperature problems have been placement of components too close to a heat source, improper heat-sinking, and a faulty heat dissipation system.

3. Pressure. The most common pressure problems are those involving varying contact resistance because of insufficient pressure being applied in a connection such as a ground, which might have to be of low resistance to minimize common-impedance interference. Lack of contact pressure, caused by the loss of temper in socket, switch, or relay springs can cause varying contact resistance.

At high altitudes avionics devices can suffer pressure-related EMI and degradation of performance when they are not pressurized. Some items such as antennas connot function within the pressure shell, and others may remain unpressurized for design expediency. If the ambient environmental pressure is low, corona discharges and high-voltage breakdowns are more apt to occur. This not only reduces performance of the equipment itself, but also produces high di/dt and dv/dt values which can couple to other circuitry by magnetic or electric fields or by conduction.

4. Friction. Triboelectricity is electrification generated by friction. Triboelectricity can produce charges which accumulate on the material until voltage is attained high enough to force a discharge across a surface or through the dielectric, causing electrical noise. Electrostatic charges on meter faces can alter the reading of the meter due to electrostatic forces on the pointer. An electrostatic charge on the tube face or plastic graticule of a cathode ray tube can deflect the electron beam and give an erroneous reading.

Friction between different insulating materials, such as cable jackets under vibration or between mechanically-driven parts using rubberized belts, ny-

lon or fiber gears, or magnetic tapes, can build up charges. Vehicles or aircraft moving on the ground can suffer from EMI generated by tire static. In the case of insulating materials, a high-resistance coating can be used to drain charges to ground. In the case of moving belts, small radioactive sources are available to ionize the air near the belt or tape so the charges can pass to ground.

Electrostatic charges can be built up by contact with a stream of high-speed air, as happens with automobiles and aircraft. Paths to ground and static dischargers should be provided for aerospace vehicles to prevent excessive charge build-up and to minimize interference with electronic equipment. This can be accomplished in airplanes by using little tubelike conductive rubber devices that hang from trailing edges of wings and tail, serving as corona points that drain accumulated charge back into the air.

5. Light. Some materials generate a voltage, change resistance, or emit electrons when exposed to light. Usually devices intentionally using these properties are housed to exclude most interference. The use of non-opaque containers for semiconductors may cause erratic circuit operation as some semiconductors have strong photoelectric qualities. Where ionization of a gas such as oxygen may take place between conductors with a potential difference, exposure to light might significantly lower the voltage or time required for sparkover. Gaseous voltage regulator tubes are highly susceptible to this problem.

EFFECT ON EQUIPMENT/SYSTEM PERFORMANCE

The next two sections will deal with the effects on equipment and system performance of the previously mentioned EMI qualities.

a. Interfacing. A particular component may be designed to have little EMI-caused degradation from its own parts, but when EMI energy can be coupled through an interface medium, it may still suffer or cause interference involving other components whether remote or in close proximity.

b. Discontinuities. Even basic design must consider the probability of discontinuities occurring anywhere within the total system. Some of the problems which may occur are:

1. Intentionally low-resistance contacts may develop into high-resistance contacts at pressure or soldered connections or at switch contacts.

2. Intentionally high-resistance contacts may develop into low-resistance contacts at points of insulation or part breakdown.

3. Geometric discontinuities in conductors and between conductors create local circuits, each with its own natural resonance caused by distributed capacitance and inductance. These circuits can be set into oscillation by shock or electromagnetic excitation.

4. Non-linear elements may bring about the generation of additional frequencies, depending upon the source of excitation. Again, component design may not consider external source effect on non-linear elements such as diodes, thermistors, thyristors, incandescent lamps, varactors, square-loop magnetic material devices, and all multi-terminal semiconductor, and vacuum or gasfilled tubes.

The effects of all the preceding EMC problems can vary from being a nui-

sance to causing a catastrophic mission or system failure. Radio noises like hum, key clicks, static, CW tones, garbled words, hiss, scratching or beeping sounds, and other background noise in the headphones may be annoying, but a human operator can compensate for most random output variations. Because automatic equipment might not compensate, the result can be increased errors in communication, navigation and control, or reduced probability of target detection, acquisition, or kill.

Equipments are sometimes designed with the expectation that new "growth mission" operational requirements may be added in the future, that random and unpredictable noise may occur, and that equipment characteristics may vary because of manufacturing tolerances, normal use, age, and maintenance.

Addition of noise frequencies to the desired signal frequencies can overload circuitry, requiring a time lag for recovery. These recovery lags can be a result of conducted or radiated energy from internal or external sources.

Transients have caused missile destruction, loss of computer synchronization or data storage, loss of guidance due to damaged transistors, and accidental triggering of controls.

It is relatively simple to predict all frequencies to be produced but their magnitude is very difficult to predict. Measurement of the signals is often the most practical approach because of the large number of factors such as the frequency characteristics of the circuits and components, the shape and point of operation on non-linear characteristics curves, the relative strength of signals, and the bandpass of the transmission lines.

DESIGN CONSIDERATIONS FOR EMC

The preceding sections have concentrated primarily on parts by themselves. The following will include circuit considerations in cabling, transistor circuitry design, and an EMC-conscious power converter and audio amplifier design.

Since many electronic circuits are constructed with a ground plane carrying the return circuit, the following approximation is useful:

$$L = 5.06 \ln[(4h/d) \times 10^{-9}] \text{ henrys per inch} \tag{15-30}$$

where h/d is the ratio of wire (centerline) spacing from the ground plane to the wire diameter. More exact formulas are available from handbooks, but the one quoted illustrates that inductance and flux linkages are kept down by close spacing of a conductor to its return, whether the return be another wire or a ground plane.

It is appropriate at this time to go back to the physical concept of mutual inductance as illustrated by:

$$M = K(L_1 L_2)^{1/2} \tag{15-31}$$

Here it is seen that the mutual inductance between two circuits is directly related to the self-inductance of the two circuits involved as well as the coupling (K)

between them. Mutual inductance may thus be controlled by reducing the self-inductance, L_1 and L_2, of each separate circuit by normal methods of minimizing circuit area. Coupling (K) may also be reduced to minimize the total mutual inductance by separating the circuits physically or by simply using a twisted pair or pairs for one or both circuits.

For example, assume that a harness contains a number of wires in which the two pairs of interest are located as shown in Figure 15-38. If No. 20 wire is assumed and the loading of the other circuit wires present may be neglected, then the following values are approximately true for a cable run of eight feet:

Circuit A (wires 1 and 2) self-inductance $L_A = 4\mu H$
Circuit B (wires 3 and 4) self-inductance $L_B = 4\mu H$
Coupling factor (Circuit A to Circuit B) $K = 1$

then:

$$M = K(L_A L_B)^{1/2} = 4\mu H \tag{15-32}$$

Now, assume the following circuit characteristics:

Circuit A is a 28 volt DC battery line with a 1-ampere 10-kHz component caused by a load

Circuit B is a low-impedance sensor, such as a current shunt, to a high-impedance input circuit

Thus, the Circuit A voltage due to the 10 kHz current is low and no capacitive coupling is considered; also, all of the induced voltage in Circuit B appears at the high-impedance end of the circuit.

The induced voltage is:

$$e_B = -4 \times 10^{-6} \times (2\pi \times 10^4) \times 1.414 \cos \omega t \tag{15-33}$$

Where:

$$\omega = 2\pi 10{,}000$$

$$e_B = -0.25 \cos \omega t \text{ (volts)}$$

or:

$$e_{B_{rms}} = 0.178 \text{ volt}$$

Now, if wires 1 and 3 are chosen for Circuit A′, and 2 and 4 are chosen for Circuit B′, the following relationships are approximately true (see Figure 15-38):

$$L_{A'} = L_{B'} = 1.3\mu H$$

$$K' = 0.4$$

Therefore:

$$M' = 0.4 \times 1.3 = 0.5\mu H$$

and

$$e_{B'_{rms}} = 0.022 \text{ volt}$$

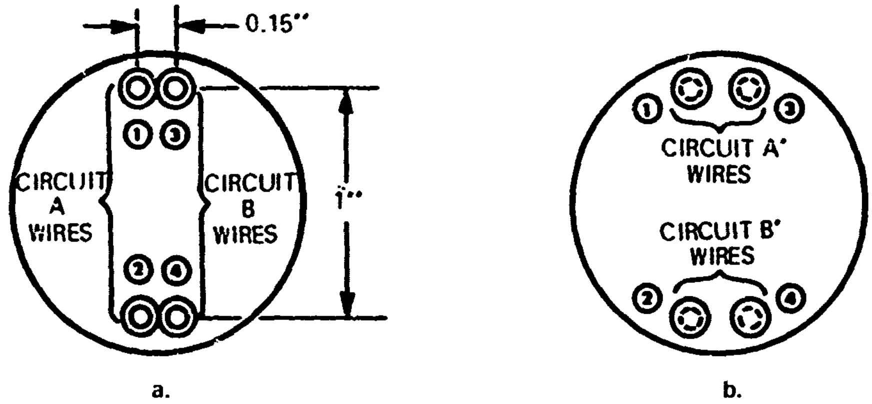


FIGURE 15-38 CABLE CROSS-SECTION

Thus, just the outlined change in cable wire routing has reduced the inductively coupled voltage from 0.18 volt to 0.022 volt rms, or by a reduction of 18.3 dB. About 10 dB results from the reduction in the self-inductance of the circuits and 8.3 dB results from the reduction in K by separation. Coupling can be reduced to much lower levels just by twisting wires 2 and 4 (Circuit B′), which may result in an additional 40 dB reduction in the induced voltage to approximately 0.22 millivolt rms.

When reduction levels of this magnitude are considered, it is necessary to examine the balance of Circuit B′, including the balance of the terminations to earth at both ends and the uniformity of spacing to Circuit A′.

If the twisted pair in Circuit B′ is considered as one wire, it is found that the mutual inductance between the circuits is approximately 0.25μH. Thus, the voltage difference between the ends of Circuit B′ is approximately 11 millivolts,

which is called longitudinal induction. If Circuit B' has a balance figure of 30 dB, then a line-to-line voltage of approximately 0.36 millivolt will result.

The balance ratio used here is:

$$dB - balance = 20 \log \frac{E_{longitudinal}}{E_{line\text{-}to\text{-}line}} \tag{15-34}$$

Thus, unless good practices maintain all impedances associated with Circuit B' balanced with respect to ground, the full benefit of twisting Circuit B' may not be realized.

Circuits that are sensitive to a given voltage of interference are readily affected by high frequency or fast changing pulses in the interfering circuit. This follows from the fact that the voltage, e_1, induced in one circuit as a function of current, i_2, in another is:

$$e_1 = M \frac{di_2}{dt} \tag{15-35}$$

Therefore, coupling due to mutual inductance, in general, becomes more serious as the frequency of sinusoidal currents increases and as the rise and fall time of transient currents decrease.

External radiation from any source is always a direct func·· · of the radiating circuit area, whether it is a voltage (E) field or current (H) field source. It is therefore usually necessary and wise to decouple stage by stage. Decoupling methods discussed herein are pointed toward isolation of potential interference voltages and currents.

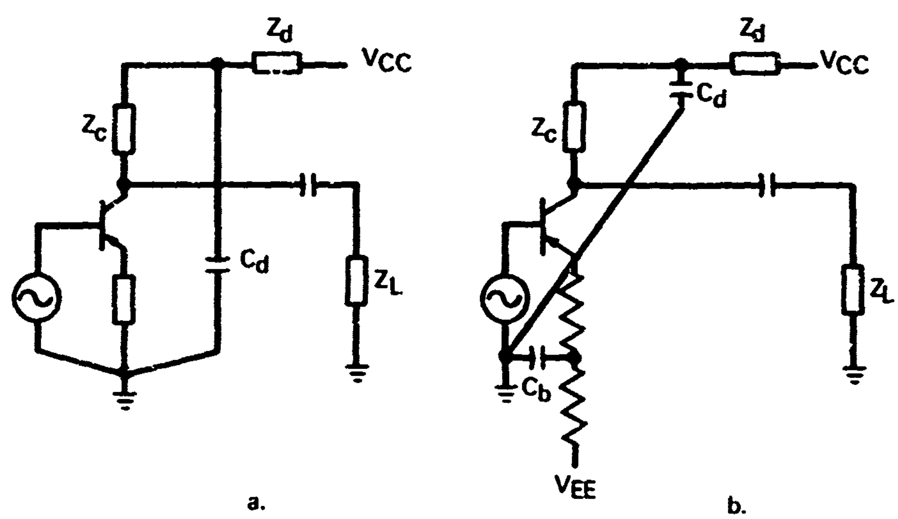


FIGURE 15-39 OUTPUT STAGE DECOUPLING

For high-current stages such as a power output stage, shown in Figure 15-39, the collector current should be supplied from a low-impedance source. Signal currents that flow through Z_c are supplied by the charge on decoupling capacitor C_d and power supply V_{cc} in series with Z_d. If signal current flows through the source of V_{cc}, there will be a voltage drop in the source and in the interconnecting wiring. This voltage will then affect all other circuits connected to that supply and objectionable interaction may result. In addition, the current through the wiring may induce voltage in other wires. Therefore, a low-impedance path, C_d is provided. A series impedance, Z_d, is provided to raise the impedance of the path and make the power supply a constant-current source. There will be a frequency below which the impedance of C_d and Z_d will force signal currents to flow in the power supply. The value of C_d and Z_d should be selected so that this frequency is sufficiently low that signal currents do not appear in the power supply and wiring.

The signal current that flows through Z_L is the desired output of the device. This current should also be returned to the emitter with a minimum of disturbance to other circuits. If the emitter and the load are both connected to the chassis or circuit board ground, the return current can provide a voltage drop in the ground bus impedance that might interfere with other circuits. A loop is also created that can act as a transformer to couple into other loops. For low-frequency circuits, where the signal system is grounded at only one point, the best return path is a wire twisted with the other wire to Z_L. At high frequencies, the capacitance of the lead which connects to Z_L will cause currents to flow to the chassis along its length and to adjacent wires. This current, too, must get back to the emitter. The solution is to provide a shield around the cable to establish a controlled capacitance. The return current for the cable capacitance can then be returned to the emitter by connecting the shield to the emitter. The return current for the load can also be passed through the shield, particularly if either the load or the emitter can be floating. If both emitter and load are grounded, a small percentage of the return current will pass through interchassis grounds. Twisted pairs inside shields and transformer coupling should be considered for decreasing this coupling problem. These problems are only mentioned here to give a more complete consideration of the signal currents supplied by a high-current stage.

Figure 15-39b shows the emitter bypass method used with two-supply biasing. With the connection shown, the signal current flows through the emitter bypass capacitor C_b. It might seem preferable to connect C_d to the emitter side of C_b so that the collector current does not pass through the emitter bypass capacitor. However, that connection allows disturbances on the power supplied to be coupled into the base emitter signal loop, hence the method shown in Figure 15-39b is preferred.

Interference involving tuned output currents can be minimized by connecting the resonating capacitance across the tuning coil rather than between collector and ground. The two configurations are shown in Figure 15-40. With the capacitor across the coil (Figure 15-40a), current through the decoupling capacitor at resonance is $e_o/Q\omega L$, where Q is the Q of the tank circuit, ωL is the

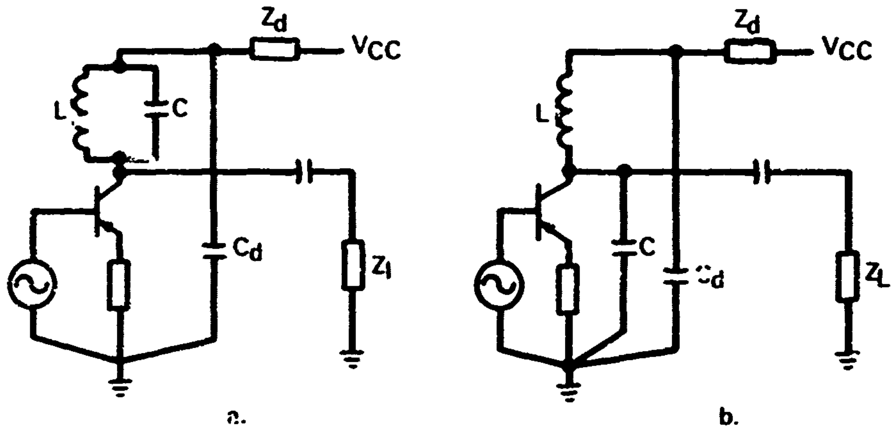


FIGURE 15-40 TUNED OUTPUT STAGE DECOUPLING

impedance of one arm of the tank at resonance, and e_o is the output voltage. If the capacitor is instead connected to ground (Figure 15-40b), C_d becomes part of the series resonant circuit, and current through it is e_o/L, which is higher by a factor Q, which may be approximately 100. Hence, for easier decoupling, the former connection is preferred. In many cases, most of the current passes through distributed capacitance to the chassis, and for those cases C_d will have to be large enough to handle the full tank current.

If the amplifier has signals at a frequency such that $\omega^2 = 1/L(C+C_d)$, then series resonance of Z, C, and C_d as a pi network can give an objectionable amount of voltage across the decoupling capacitor. The amount of voltage will depend on Z_L and Z_d. To approximate the effect, consider the impedance of both to be infinite; Then the current through C_d is the short circuit output current of the transistor. Finite values of Z_c and Z_d will reduce this current appreciably.

Emitter-follower stages should be provided with a collector decoupling network to return the collector signal current to the emitter without flowing through the collector supply. Figure 15-41 shows the collector bypassed to the emitter ground. However, if $Z_L < R_e$, which is a typical case when a separate emitter supply is used, current through the chassis can be reduced by returning C_d to the point at which the load current is returned to the chassis

The interstage coupling of a pair of transistors is shown in Figure 15-42a. The subsequent transistor is represented by its input impedance, Z_i, and its base biasing resistors by R_1 and R_2. The function of this stage is to amplify the input signal represented by e_s and supply maximum current in Z_i and minimum current to the impedances in common with other circuits. At the same time, disturbances on the supplies or in the chassis impedances should supply minimum current to Z_i.

The emitter is shown bypassed to the input signal ground to return the base current signal directly to the driving source without going through the chassis

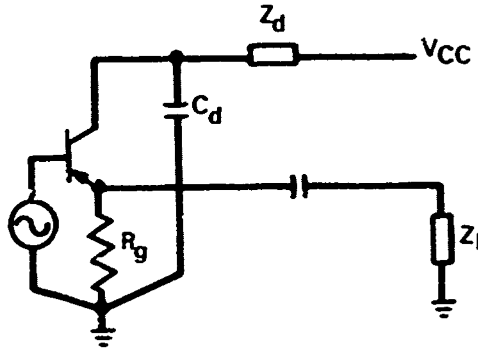


FIGURE 15-41 EMITTER-FOLLOWER DECOUPLING

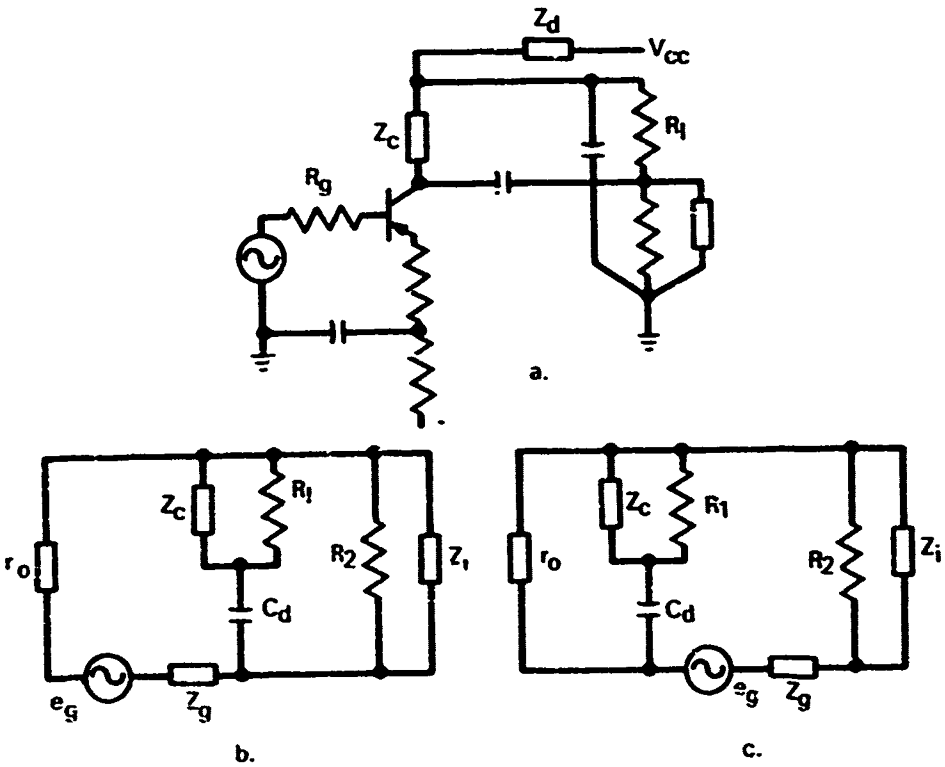


FIGURE 15-42 INTERSTAGE DECOUPLING

impedance. The ground point of C_d has conflicting requirements. In the connection shown, all of the transistor current flows through the chassis so that there may be coupling to other stages. If C_d is connected back to the first-stage ground, this chassis current is reduced by the amount of current that flows through Z_c and R_1. If a current exists in the chassis due to some other source, however, the configuration of Figure 15-42a minimizes the amplification of this undesired current by the following stages. This is demonstrated in equivalent circuits shown in Figures 15-42b and c. The transistor has been replaced by its output impedance, r_o. The circuit of Figure 15-42a is shown in Figure 15-42b where e_g and z_g represent the interference source, the chassis currents. Any current that passes through z_i must pass through r_o, which is usually a high impedance. However, in Figure 15-42c, which represents the circuit with C_d returned to the emitter ground, the current through Z_i can flow through R_1 and Z_c which are usually much lower impedances than r_o.

When flip-flops change state, the current required from the supply voltages changes momentarily. This pulse is rich in high-frequency components and can couple into wires adjacent to those carrying the supply current. These transients should be kept on the flip-flop board with a decoupling network consisting of shunt C and series R or series L. Where series L is used, the filter ringing possibilities must be carefully examined. Where possible, the circuit and board configurations should include both elements of the flip-flop so that the local current transfer between these elements necessitates a minimum of energy storage for the small fraction of time that both elements are simultaneously on or off.

Some computer circuits use a reference voltage to bias clamping diodes to obtain constant-level pulses. The resulting pulse currents in the reference supply and wiring are a source of interfering signals. It is recognized that a series impedance for decoupling can spoil the reference level. However, a capacitor suitable to the frequency requirements to ground on each board will usually decrease the amount of high-frequency current in the reference supply and wiring. In this case, the power supply source impedance at the point of decoupling must be considered in selecting the size of the decoupling capacitor.

Following is an example of the application of EMC techniques to the functional circuits of an equipment such as the power converter and audio amplifier shown in Figure 15-43.

Specifications for the audio amplifier are:

1. Supply voltage: 28 volts
2. Switchable audio frequency inputs for
   (a) A long line connected to a remote audio system
   (b) A low level microphone
3. Audio frequency outputs for:
   (a) Supplying five watts to remote speakers
   (b) Providing a tape recorder output
4. Quality reproduction of voice is required

5. Must meet all applicable military specifications for conducted and radiation interference over the frequency range of 0.15 to 400 MHz

6. The input power, audio input, and recorder may not be grounded in order to achieve EMI control.

The functional circuitry shown in Figure 15-43 consists of an audio preamplifier driving an audio power amplifier, with both powered by a DC-to-DC converter.

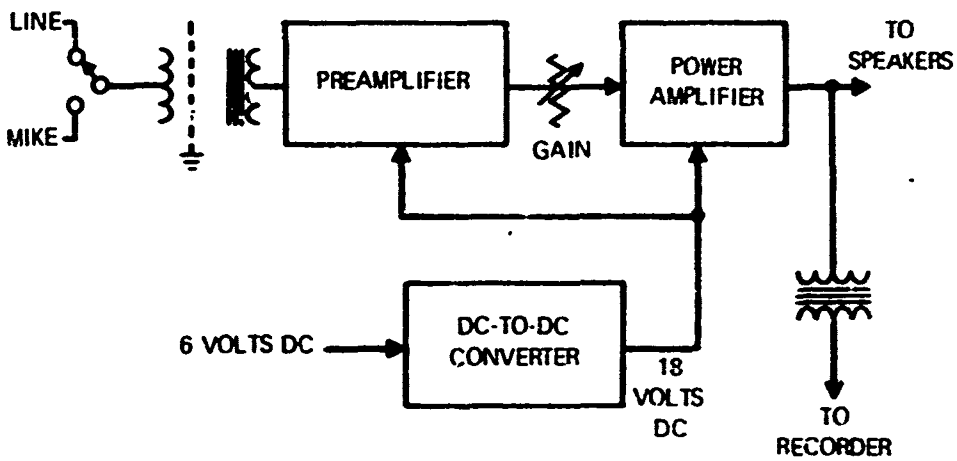


FIGURE 15-43 EMC MEASURES IN AN AUDIO AMPLIFIER AND POWER SUPPLY

A well-shielded input transformer is used to open any ground loops to the distant audio system or microphone. High gain must be used in the preamplifier since the typical microphone has a very low power output. Therefore, the input circuitry, including the input transformer, is very susceptible to interference. An electrostatic shield is used between the primary and secondary windings of the transformer to prevent electrostatic coupling of longitudinal interference voltage on the input lines into the preamplifier. Longitudinal voltages are those that have the same instantaneous magnitude and polarity on both conductors. When this is so, they can cause no current throught the transformer primary winding, but they could couple electrostatically to the secondary winding unless the input wiring has an electrostatic shield inside the transformer. To ensure capacitive balance of the transmission line to the distant audio system or to the microphone, these lines should have an electrostatic shield and be twisted together to provide magnetic balance. The input transformer should be enclosed in magnetic shields and should preferably be of semi-toroidal construction. It may be desirable to enclose this transformer in a simple sheet iron enclosure or provide a shading ring to prevent it from picking up power supply magnetic interference. The gain control should follow the preamplifier rather than precede it. Otherwise the noise contribution and interference-pickup of the control and its wiring will

be an appreciable portion of the low-level signal input.

Circuit connections to common buses and circuit decoupling from the common power supply should be designed to minimize common-impedance coupling of interference and to eliminate amplifier instability due to feedback paths. To simplify this, each amplifier stage should be designed for the minimum permissible audio bandwidth that will result in the specified overall amplifier bandwidth.

The DC-to-DC converter has been sketched in Figure 15-44. It has a semiconductor chopper that supplies a 6 volt, 1000 Hertz switching rate, square-wave voltage to the power transformer. Switching in the chopper occurs at points of saturation of the power transformer core. The secondary of this transformer feeds a semiconductor bridge rectifier, which, in turn, feeds the output filter that provides the 18 volts DC used to power the preamplifier and power amplifier.

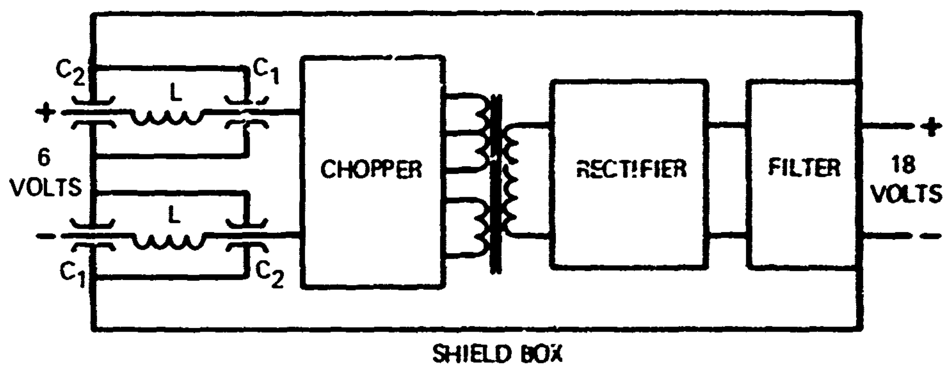


FIGURE 15-44. EMC MEASURES FOR A DC-TO-DC POWER SUPPLY

The chopper, the transformer, and the rectifier cause switching transients with rise times in the order of one microsecond. Because the transformer core saturates, it will radiate a strong magnetic field. To meet EMC requirements, escape of this interference from the power supply shield box must be prevented. This can be accomplished by providing a completely enclosed shield box of high permeability magnetic material around the power supply.

C_1, C_2, and L form a pi filter on each side of the primary power input line to prevent the escape of conducted interference. Filters of this type present a reactance to the connected circuits in the stop band and, therefore, reflect the interference. Unless they are carefully made and grounded, they can also have resonances that permit the transmission of interferences at one or more of the resonant frequencies. A type of filter that absorbs interference usually consists of no more than a length of conductor embedded in a lossy magnetic material. Ideally, there would be a perfect impedance match to the connected circuits at interference frequencies so all interference would be absorbed, and also having infinite attenuation for interference and no attenuation for the desired frequency passband. Similar interference filters should be used on the power supply output leads. Note that separate shield cans are provided on the filter inductors to pre-

vent either the pickup or radiation of interference.

To reduce the magnetic field radiated from a power transformer in this application, the power transformer is frequently of toroidal construction or is encased in its own magnetic shield. Only modest electrostatic shielding is necessary for the audio amplifier circuits.

It can be seen that the power supply transformer also fulfills the requirement that the primary source not be grounded, thus preventing ground loops through the power system.

All of the interference control measures discussed for the audio amplifier and its power supply apply to the same type of circuits in the amplitude modulated (AM) transmitter shown in Figure 15-45, but radio frequency considerations are added. At radio frequencies, shielding and decoupling become more difficult because the inductance of even short conductors presents appreciable impedance. The same principles apply but shields and grounding conductors must make short and direct connections to a sheet of metal that serves a ground plane rather than the ground tree used in low frequency circuits. Circuit layouts on the ground plane are arranged for minimum radiated and conductive coupling. This is augmented by the erection of suitable shield walls between the circuits. These walls are soldered or otherwise bonded directly to the ground plane at many points. Radio frequency coils are oriented with respect to each other for minimum coupling, are constructed as toroids, or are enclosed in shield cans bonded directly to the grounded plane. Radio frequency transmission lines are usually unbalanced and are run as close to the ground plane as possible.

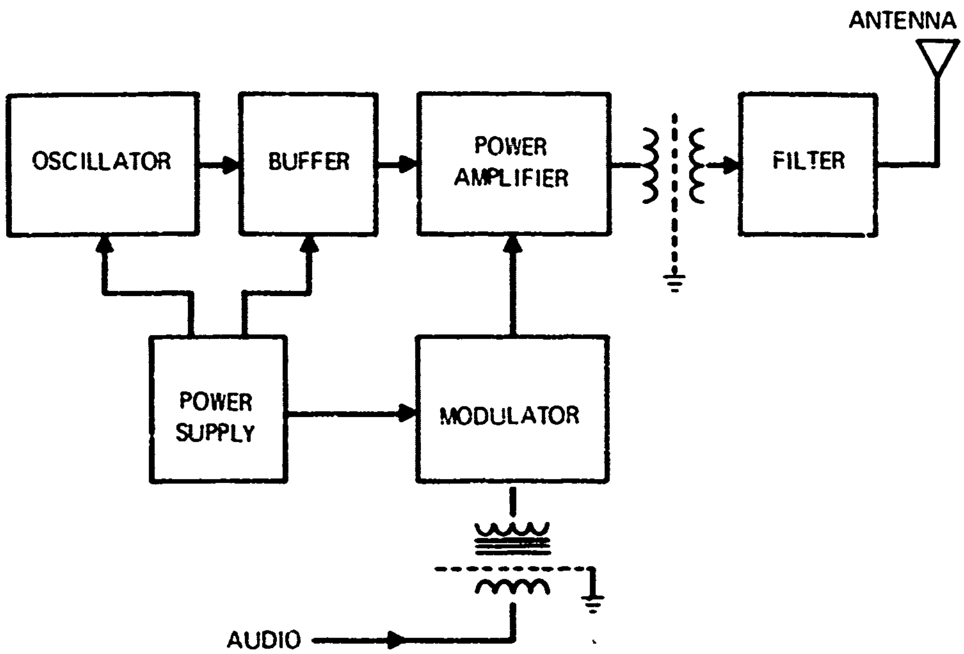


FIGURE 15-45 EMC MEASURES IN AN AM TRANSMITTER

Radio transmission lines between circuits on different ground planes or in different equipments are usually unbalanced coaxial lines, because well-balanced lines are difficult to achieve at radio frequencies in the limited space usually available. As a result, the radio frequency ground plane is constructed for the whole radio frequency system and all circuit ground planes are bonded to this with the shortest and largest conductors practicable.

In radio-frequency systems, emphasis is generally on prevention of spurious or interfering electromagnetic radiation. This usually requires total enclosure of RF circuits, with filters or conductors entering those enclosures designed to prevent the escape of RF currents. This is particularly true of the power amplifier stage of a transmitter where high power harmonics are produced in normal operation of the amplifier. A transformer with an electrostatic shield followed by a harmonic suppression filter before the antenna suppresses the radiation of harmonics to permissible levels. To ensure that the final stage input is low in harmonic and other spurious RF energy, a buffer amplifier is used along with interstage decoupling and shielding.

DIGITAL DATA SYSTEMS CONSIDERATIONS

Recent advances in digital data transmission and the rapid development of computer technology and information theory now make it possible to tap the potential of electronic communication much more efficiently than ever before. Communication systems, in a wide sense of the word, are no longer restricted to verbalized message-type information; they are taking on the function of control systems, involving the exchange of digital data between computers which automatically process, display, and act upon incoming data from various inputs. Channel efficiency is considerably increased by setting up a single automated communication system possessing time-sharing capability in which all forms of information from all participants are handled in a uniform binary code.

The present trend in flight vehicle design is toward the use of digital data techniques for communication, data processing, indicator and control systems. Most modern combat aircraft use a central data processing unit that functions as a central control and interfacing unit for all radio data link, navigation, flight stabilization, target detection, acquisition, tracking, and weapon control systems aboard. Modern-day requirements for high data rates lead to systems having short pulse duration and wide bandwidth, which in turn increases the potential for emission and susceptibility problems.

Equipments that use digital techniques are subject to degradation of data when interference appears in their power, control, or signal leads. Digital data equipments, which contain large numbers of solid-state switching circuits, are also capable of emitting conducted or radiated interference. The emission and susceptibility level of digital data equipments will vary depending upon design, construction, installation, and proximity to interference or susceptible circuitry.

EMI/EMS EFFECTS IN DIGITAL DATA SYSTEMS

When a digital data equipment is part of a complex system consisting of many electronic units, its operation should not be allowed to interfere with other equipments, and it should be unresponsive to extraneous influences in the surrounding electromagnetic environment. To achieve compatibility, digital data systems should be designed and tested for control of interference emission and susceptibility characteristics. Emission and susceptibility of the equipment can be controlled by isolating the critical circuits and by appropriate circuit design, which includes RF filtering of interference and selection of circuit logic that minimizes EMI generation or susceptibility.

Digital data systems use a binary system of numbers to perform their required functions. Ideally, information in a digital data system should consist of bistatic circuit conditions in which each circuit element represents either of two all-or-nothing states so that information is in the form of binary "words" consisting of a series of 1's and 0's. A binary 1 may be represented by a certain voltage level (positive or negative), or by a pulse with a defined amplitude, shape, or phase, a binary 0 may be represented by a voltage level opposite in polarity to that of a 1, the absence of a level, the absence of a pulse, or by a pulse of the 1 type but at a different phase. Digital data circuits are designed to switch states from one condition to the other with minimum transition time.

Binary circuits lend themselves to use in thresholding or comparator circuits capable of restoring the integrity of pulses or levels that have become degraded in level or shape by noise, bandwidth limitations, or other circuit effects. In such a circuit, it is necessary only for the digital data information level to reach a value sufficient to satisfy a switching threshold or comparator circuit, and the pulse or level will be restored thereby to a full-amplitude, relatively noise-free condition. It is this characteristic, however, that permits EMI to introduce data errors. If EMI exceeds the switching threshold, or so degrades a signal that it fails to reach the threshold, the EMI can be quantized into a full-level bit error.

Noise Generation and Susceptibility

To achieve high switching speeds, digital equipments commonly use low level signal currents or voltages so that transition times between the states representing 1 and 0 can be kept short. High rates of change produce switching impulse noise. This may require that a trade-off be made between switching speeds and the EMI effects of noise and switching transients. The predominant interference generated by a digital equipment can be attributed to the repetitive operation of a multitude of switching circuits having fast rise times. The interference is directly related to the organization of the machine, its logic functions, timing, and basic circuitry. In addition, a solid-state device when conducting produces "white" noise as a consequence of current flow in the device. Computers may contain a vast number of circuit elements whose switching operations are synchronized by clock timing logic. A computer, therefore, can be a prolific source of broadband noise.

The noise margin and noise immunity parameters of gating circuitry used in digital devices are measures of the gate's susceptibility to noise signals. Noise margin is defined as the magnitude in volts of pulse noise, which, when appear-

ing at the input of a digital gate and riding on the worst case logic level, will cause a significant reaction at the output of the gate. DC noise margin, as in wide, slow rise time noise pulses, is the difference between the worst case logic voltage level and the worst case switching threshold voltage of the gate. Transients or AC noise margin, as in fast rise time noise pulses, is, in most cases, less than the DC noise margin.

Noise immunity is a measure of a gate's immunity to noise generated by neighboring gates. Noise immunity is indicated as follows:

$$\text{Noise immunity} = \frac{\text{worst case noise margin}}{\text{maximum logic voltage swing}} \times 100\% \qquad (15\text{-}41)$$

Crosstalk

Crosstalk in a digital circuit may occur in two ways: internally via coupling phenomena within the solid state device itself, or externally via cables and connectors of associated circuitry.

Internal coupling occurs as a consequence of parasitic mutual capacitance and inductance inherent in the semiconductor device. The isolation between input and output of semiconductor devices, the circuit elements most commonly used in digital data systems, is notoriously poor. This inherent characteristic may result in undesirable coupling from one input to another, or from an input to an output. This coupling may also result in crosstalk between two gates in the same integrated circuit package. These problems indicate the necessity for an investigation of the manner in which unused terminals are to be handled. A decision must be made as to whether they can be allowed to float or whether they should be tied to some bias voltage or to ground.

External coupling is due to mutual capacitance and inductance of interconnecting lines and conductors. High rates of change of voltage or current on these conductors will cause crosstalk between them. Given the mutual inductance (Lm) and the mutual capacitance (Cm) of two interconnecting conductors, the voltage or current crosstalk may be estimated by Lm di/dt and Cm dv/dt.

The effect of crosstalk is to cause noise, usually in the form of differentiated leading and trailing edges of input signals, to appear on the output (or other inputs) of a gate even though the gate inputs did not satisfy the switching logic. A crosstalk signal of sufficient magnitude and width may be amplified and shaped by a string of gates so that it results in a logic signal that causes an error.

Magnetic Materials

Frequent use is made of magnetic materials as information elements in digital data processing systems. Magnetic tapes, discs, or drums may be used as input/output or storage devices, and magnetic toroids are frequently used in shift register, decoder, buffer storage, and memory circuits. Because the mag-

netic mass and flux density is often quite small, these magnetic materials are easily influenced by extraneous magnetic fields. An alternating EMI field can erase the data stored in magnetic materials; a DC EMI field can bias the magnetic materials toward an "all ones" or "all zeroes" state; and magnetic transients can produce digital bit errors. The portions of digital data processing systems that use magnetic materials must therefore be protected from internal and external magnetic fields.

Electrostatic Effects

Persons accustomed to handling solid state devices are aware that unless precautions are taken, certain types of diodes and transistors can be degraded by a static charge accumulated on the human hand. The electrostatic effects become less troublesome after the device is installed, because of the (usually) low resistance of associated circuitry. However, cases have occurred of impaired computer performance attributed to static charges on a plastic cover over a row of logic cards. Because triboelectric charges can become quite large in an aircraft, designers must consider possible effects on digital data systems.

Power and Ground Circuit Transients

High rates of change of current in the power and ground terminals of digital circuits may cause voltage disturbances in the power and ground distribution systems which may result in the propagation of an error signal. Because a number of circuits may be packaged to form one module, a power supply decoupling capacitor may be necessary within the module. When the circuits are grouped into modules and each module contains power supply bypass capacitors, the currents to be evaluated for EMI are:

1. Ground currents that leave the module and flow into the system ground
2. Signal currents that flow in the bypass capacitor mounted in the module

High speed switching circuits may place a large transient current demand upon power supplies during transition from one logic state to the other. Knowledge of the rate of change of these currents will allow the system designer to calculate, approximately, the tolerable impedance of the bypass capacitor and the system ground. Measurement of the area under the waveform of the current that passes through the bypass capacitor gives the charge drawn during switching. This measurement allows the designer to determine the value of the bypass capacitor necessary in the circuit module.

The path from the module to system ground must be a low impedance. If the module is a printed circuit card, it is almost always necessary to use more than one of the connector pins as a ground return. The common ground return for groups of modules should also be designed for low impedance.

Susceptibility of a digital circuit to disturbances in the power and ground systems may be determined by introducing a disturbing pulse between the ground pin of the module and the system ground, or between the power pin and

the system power. If the logic circuit under test is one of a string of gates, the width and amplitude of the disturbing pulse may be varied to determine the minimum pulse that will result in the propagation of an erroneous logic signal.

MINIMIZING DIGITAL DATA ERRORS

An analog communication or data system can often "lose" an appreciable portion of a data word to interference without the overall usefulness of the individual signal transmission and reception being degraded below an acceptable level. For verbalized communication in plain language, a word with parts missing or in error can often be recognized and restituted correctly by a human operator. Electromechanical analog systems can sometimes minimize the effects of EMI by using electrical filters and mechanical damping. A digital data system, however, operates differently as a consequence of signal degradation. The introduction of an error bit into a word (a 1 converted to a 0, or vice versa) converts the entire word into an error word. The consequences of an error bit in a digital data word can vary, depending upon the position of the bit in the word. Yet EMI is as likely to cause an error bit to appear in one place as any other. A digital data system must therefore be designed to recognize an error word and to reject the word in its entirety. If the error word were processed into the data, it possibly could bring about a degradation far greater in magnitude than that of the original error, for example, cause dumping of a stored program.

Digital data devices in flight vehicle systems are expected to operate in close proximity to other systems which use high amplitude pulses. Radar, Tacan, IFF, beacon transponders, and tactical data links are typical of potential sources of pulse interference. The pulsed or bistatic logic used in digital circuits can easily be triggered by pulses from these systems, or from electrical or magnetic transients on power, control, or signal leads.

In typical digital data equipments, some circuits have an inherent immunity to malfunction under intense electromagnetic influence. Relatively invulnerable circuits include high level circuits such as flip-flops, line drivers, relay drivers, level inverters, and emitter followers. On the other hand, low-level circuits whose normal input is within the range of 50mV to 2V peak-to-peak, tend to malfunction when subjected to interference of moderate field intensities. Circuits in this category include tape readers and magnetic core memory sensing amplifiers. Digital data systems employing radio data links are most susceptible to degradation in the radio circuit itself rather than in the logic circuits that follow the quantization process. The EMI control measures previously discussed for receivers in general apply to the digital data receivers. Other measures are also particularly applicable to digital data systems.

Parity Error Check

The parity check method involves determining the number of binary 1's in a data word. Circuit logic can be arranged to accept either an odd number or an even number, with a position in the word reserved for the insertion of a parity bit where needed to satisfy the error-checking circuitry. If EMI should cause an ex-

traneous bit to appear, the parity error check would reject the word as containing an error. Usually the circuit logic is designed to try repetitively to read the word before finally rejecting it. The parity error check method affords no protection against error words containing two or any even number of error bits.

Data Word Redundancy

To increase the reliability of digital data reception, some data transmission systems transmit each data word twice. Two methods are in common use: series redundancy and parallel redundancy. The series method transmits each word twice in sequence over a single channel. The parallel method transmits the same word over two or more channels simultaneously. The typical radio data link may use two independent sideband channels for this purpose. In either case, the two samples of the data word are stored in buffer registers and compared bit for bit. If the two are not identical, a reception error is indicated and the word is rejected.

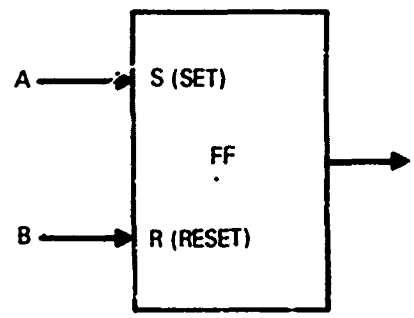
Strobing and Gating

Strobing is a process sometimes used in digital systems (including teletype) to prevent circuit switching transients from degrading the bit accuracy. Strobing consists of sampling each bit at a time the signal has reached its best 1 or 0 (mark or space) condition. The strobe sampling time is usually much shorter than the duration of the expected signal. Circuit switching can cause such effects as switching noise, "ringing" due to reactive components of circuits and filters, or slow rise and decay (bias) of pulses due to RC or RL delays. The timing of the strobe sampling circuit is adjusted so that the EMI effects of a circuit switching sequence has had time to abate before the sample is taken. The strobed sample is then used to set buffer registers, selector bars, or other storage devices that will reconstitute the signal into a noise-free state.

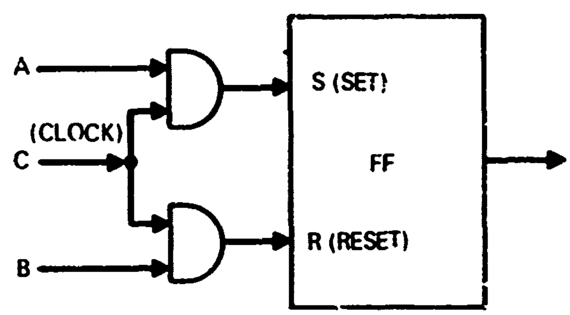
A typical application of the principal of strobing is used with the waveform that represents the output of a sense amplifier, a circuit that senses the output of a ferrite core. The ferrite core, the heart of the memory system, stores 1 or 0 bits as a function of the direction of magnetization of the core. To "read" a memory core, the two memory address conductors at which the core is located are energized simultaneously. The combined effect of the two currents is to set the addressed core to its 0 state. If the core were storing a 1, setting it to 0 produces a magnetic flux change that is inductively coupled to a sense amplifier. If the core were storing a 0 there would be no flux change and no data bit output to the sense amplifier.

Other memory cores on the same memory plane and on other planes are affected by current in only one of the two address lines. The "half select" current is insufficient to change the magnetic state of the unaddressed cores, but it does cause noise to appear in their sense amplifiers as well as that of the addressed core. Strobing is therefore used with the sense amplifiers to prevent the noise produced by the current rise in the address lines from affecting the accuracy of reading memory cores.

A gated circuit is one that is enabled at a definite time to sense the input data. The gate is normally opened by a pulse developed from the clock timing circuits and in the absence of the gating pulse, remains closed and unresponsive to noise or any other signal. For a computer to malfunction from external interference, the interfering pulse or level must be of sufficient amplitude to either subtract from or deteriorate the information pulse, or simulate a data pulse, and at the same time be in coincidence with the gating pulse.



a. SET AND RESET INPUTS NOT GATED



b. SET AND RESET INPUTS GATED BY CLOCK PULSE

FIGURE 15-46 LOGIC CIRCUIT FOR INTERFERENCE SUPPRESSION

Figure 15-46 illustrates the use of gating to minimize the likelihood of data errors. In Figure 15-45a, which does not use gated inputs to the data register flip-flop, a noise impulse on reset bus B could cause all data registers to be reset. Similarily, noise on register input A can cause that particular register to be set.

The "set" or "reset" action may take place any time that a noise impulse of sufficient magnitude appears.

Figure 15-46b shows the use of gated input logic to suppress the error rate due to noise. Input A represents the "set" order, which could be either a pulse or a level, and input B represents the "reset" bus. Input C is the clocked gating pulse. The flip-flop can be neither set nor reset by noise or any other signal unless there is an enabling pulse from the clock gating circuitry.

SUMMARY

This chapter began with a description of the primary characteristics of parts, with particular reference to their EMC properties. Many of the characteristics that cause EMC problems can be related to several different parts. It must be remembered that differences and tolerances in manufacturing processes can result in major differences between similar parts. The large amount of literature concerning each of these parts and state-of-the-art changes makes continual study necessary.

It was shown that a magnetic field can be generated by current flowing in a conductor, and this field is a potential source of interference when the magnetic field induces an undesired current in any loop of conducting materials. Twisting and shielding a transmission line were shown to reduce the external magnetic field by a substantial amount and should be considered where magnetic coupling of EMI must be avoided. The use of shading rings and core form of iron-cored parts was also discussed.

Electric coupling tends to be through stray capacitances that can be minimized by electrostatic shields. It was shown that in the case of transmission lines, capacitance balance between conductors and ground at each end would help substantially to minimize induced voltages across the transmission line load. Again, twisting the conductors and shielding them can reduce the electric field coupling.

Conducted interference basically stems from using common buses that do not have zero impedance. By grounding properly through ground buses and using isolation where necessary, the common impedance coupling difficulty can largely be avoided. Suitable decoupling circuitry can also minimize coupling among circuits where isolation cannot otherwise be achieved.

Other interference producers are temperature differences, chemical differences, friction, pressure, and light. Although these occur less often they should be considered where such phenomena are present.

Two examples show how some of the shielding and interference reduction techniques might be applied. The first example is an audio amplifier with a DC-to-DC converter power supply. Here, shielding of the low-level circuitry and balance of transmission lines is stressed. The placement and quality of magnetic amplifiers must be observed carefully throughout the design. The DC-to-DC converter is especially troublesome because of the transients generated, so heavy shielding and filtering of all leads is required. Use of toroidal power transformer and suitable isolation from ground to prevent the formation of ground loops are

also techniques for minimizing interference. In the case of a transmitter, shields and grounds are of primary importance. Magnetic, electric, and conductive couplings must be detected and suitable shielding is required: a uniform RF ground is a basic requirement to prevent interference among the circuits. The total enclosure is of utmost importance, and its shielding properties should be reinforced by filtering of leads and the avoidance of leaky areas like meter faces.

The amount and quality of interference reduction in the final design must be related to the purpose of the equipment and also the system as a whole. A minimum of EMC measures is desirable from the cost viewpoint, but underdesign can be even more costly. An approach involving a failure mode, effects, and criticality analysis appears desirable as the basic elements of a system evolve: this information coupled with a little engineering judgment should result in an optimum design of circuits and components.

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NAVAL AIR SYSTEMS COMMAND

ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 16

PUBLISHED BY DIRECTION OF COMMANDER, NAVAL AIR SYSTEMS COMMAND

CHAPTER 16
EMC DESIGN AND PLANNING CONSIDERATIONS APPLIED TO AIRCRAFT SYSTEMS

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ILLUSTRATIONS

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AVIONICS SYSTEMS, EQUIPMENTS, AND COMPONENTS

The goal of EMC design and planning for aircraft avionics and electrical systems is to develop an aircraft in which all systems and equipments function compatibly. A system is electromagnetically compatible when it can operate in its intended environment without creating interference that would affect other components of the system, and without being susceptible to interference associated with its operational environment. The goal can best be realized by knowledgeable effort being applied to EMI suppression and control during planning and design of the system. In other words, EMC should be designed in, rather than being tested in. EMC is a product of detailed processes that encompass every phase of a program from concept formulation through production to ultimate use and maintenance of the aircraft system.

Because airplanes represent a complex array of equipments, and because interference origins can be either internal or external to the aircraft, designing for electromagnetic compatibility requires careful planning and coordination. One factor that needs careful consideration is design trade-offs. Performing such trades is an essential part of an EMC program and will be covered in detail.

AVIONICS EQUIPMENT COMPLEMENTS OF TYPICAL AIRCRAFT

The equipment complements of four different types of aircraft are listed to indicate the multiplicity of equipments to be considered in EMI reduction and control:

Attack Aircraft

1. Integrated COM-NAV-IFF Package
   AN/ASQ-17
2. NAVAIDS
   AN/ARN-21, AN/ASN-19, AN/APN-141, AN/ARA-25
3. RADAR & IFF
   AN/APG-53, AN/APA-89
4. Armament control systems
5. Compass and autopilot - automatic flight control system
6. Flight systems

ASW Aircraft

1. Communications and internal communications systems ARC-51, ARC-84 ARC-94, AN/AIC-22
2. NAVAIDS
   AN/APN-70, AN/APN-117, AN/APN-153, AN/ARA-25, AN/ARN-32, AN/ARN-52, AN/ASA-13, NVA-22A, AN/ASA-47, AN/ASN-42, AN/ARD-13
3. Radar and IFF
   AN/APA-125, AN/APA-89, AN/APA-80, AN/APX-6
   AN/APX-7
4. ASW
   AN/AQA-1, AN/ARR-52, AN/ASA-16, AN/ASA-20, AN/ASA-50, AN/ASQ-19, AN/ASR-3, AN/AVQ-2, AN/AQH-1
   AN/AQA-5
5. ECM
   AN/ALD-2, AN/ULA-2
6. Compass and autopilot (PB-20N)
7. Flight systems

Fighter Type Aircraft

1. Integrated COM-NAV-IFF package
   AN/ASQ-19
2. NAVAIDS
   AN/APN-22, AN/ASN-39
3. Radar & IFF
   AN/APA-157, AN/APQ-72
4. Infrared systems
   AN/AAA-4
5. Compass and autopilot
   AN/ASA-32G
6. Flight systems
7. Radio altimeter
8. Capacitive fuel gauge systems

Small Observation Plane

1. Communications & instrument landing systems
   AN/AIC-18, AN/ARC-51, AN/ARC-54, AN/ARC-120
2. NAVAIDS
   AN/ARA-50. AN/ARA-52
3. Radar & IFF systems
   APX-64
4. Compass and autopilot system
   AN/ASN-75
5. Altimeters
6. Flight systems

MILITARY SPECIFICATION REQUIREMENTS FOR CONSTRUCTION

MIL-STD-461A Electromagnetic Interference Characteristics Requirements for Equipment, dated 1 August 1968, lists avionics equipment generally under Class I Communication-Electronic (C-E) Equipment. Such equipments include all subassemblies and parts that electromagnetically generate, transmit, convey, acquire, receive, store, process, or use information in the broadest sense. Class I equipment is divided into four subclasses as follows: Class IA includes receivers using antennas; Class IB includes transmitters using antennas; Class IC includes non-antenna C-E equipment such as counters, oscilloscopes, signal generators, RF and audio test equipment, computers, power supplies, digital equipment, electrically-operated cameras and projectors, wire terminals, image interpretation facilities, photographic processing equipment, and other electronic devices working in conjunction with Class IA and IB; Class ID includes electrical and electronic equipment and instruments that would affect mission success or safety if degraded or malfunctioned by internally generated interference or susceptibility to external fields and voltages. Class ID includes autopilots, infrared devices, flight instruments, autocompasses, and electronic engine control devices.

AIRCRAFT ELECTRICAL SYSTEMS

MIL-STD-461A classifies electrical equipment generally as Class II Non-Communication Equipment. This equipment has three subclasses: Class IIA includes equipment in which RF energy is used for purposes other than communication and is intentionally generated for other than information or control purposes; Class IIB includes electric motors, hand tools, office and kitchen equipment, laundry and repair shop equipment, and lithographic processing equipment; Class IIC includes electrically and mechanically driven accessories and engine electrical accessories such as gauges, fuel pumps, regulators, windshield wipers, gunmount motors, magnetos, and generators when tested off the engine or vehicle.

Also included under electrical systems is equipment listed as Class III Vehicles-Engine Driven Equipment. This includes under Class IIIB, Engine Generators. Electrical systems in Class IV are overhead power lines, which are not directly related to aircraft systems but are important in considering overall ambient electromagnetic energy.

TYPES AND USE OF AIRCRAFT POWER SYSTEMS

The primary power system of an aircraft is the electrical system whose generators are driven by the aircraft propulsion engines. Power conversion systems powered by the primary gnerators are part of the primary power system when they are not part of utilization systems.

MIL-STD-704(A) establishes standards for characteristics and use of aircraft electrical power. It defines and details requirements relating to voltage and frequency deviation, phase shift, ripple, surges, spikes, harmonic content, and other modulation or transient conditions that affect EMC.

ELECTRICAL SYSTEM REQUIREMENTS FOR CONSTRUCTION

MIL-STD-704(A) specifies that the aircraft AC power system shall be a 3-phase, 4-wire "Y" system, having a nominal voltage of 115/200 volts and a nominal frequency of 400 Hz. The neutral point of the source of power is to be connected to ground and the ground is to be considered the fourth conductor.

DC power systems that conform to military specifications shall be a 2-wire, grounded system having a nominal voltage of 28 volts. The negative of the power source is to be connected to ground and the ground is to be considered the second conductor.

Power using equipment must maintain specified performance when using power with the characteristics specified in Section 5 of MIL-STD-704A, without degrading the power characteristics below the specified limits. When power having other characteristics or needing closer tolerances than those specified by MIL-STD-704A is required, the conversion equipment shall be part of the using equipment. Using equipment designed for a specific aircraft may deviate from these requirements only upon approval of the procuring activity. Using equipment specifications must specify which of the types of power is required. Aircraft equipments may require one or both of these types of power. No other types of input power may be used without written permission from the procuring activity.

MIL-STD-704(A) general requirements specify that aircraft power systems shall be so installed and so protected that the failure of any power source, and its disconnection from the system, will not impair performance of the remaining power sources.

INSTALLATION OF WIRING IN AIRCRAFT

INTERCONNECTION OF AVIONICS/ELECTRICAL EQUIPMENT

Wiring in flight vehicle avionics and electrical systems has evolved from relatively simple installations to modern integrated complexes in contemporary construction. Avionics and electrical systems are subjected to ambient electromagnetic fields of complex scope and frequency. Much has been done to improve compatibility at component, equipment, and system levels. These advances must be accompanied by corresponding improvements in wiring and cabling.

Airframe manufacturers are confronted with installation problems in which the interconnecting wire coupling effects upon any of the equipments can only

be estimated. Precautions include requirements for special wiring (other than single conductor), threshold susceptibility values over a specified frequency range, and characteristics of conducted and radiated energy over a broad frequency range. Control of EMI coupling effects in airframe wiring can best be achieved by treating the wiring as a subsystem. Special installation requirements become necessary because of signal levels and circuit impedances.

The method of interconnecting avionics and electrical equipments in a flight vehicle depends in part upon whether the particular wire or cable in question becomes a potential receiver or transmitter of unwanted energy. Obviously, a wire associated with susceptible circuits must be isolated from one carrying electrical currents or potentials capable of causing interference. Isolation is a key factor in achieving electromagnetic compatibility in airframe wiring installation. For example, a wire applying 28 volts to a lamp would not be susceptible to a wire applying 115 volts to a motor. However, if the 28 volt wire is connected to a servo-amplifier, then a degree of susceptibility might exist.

Wiring Design for EMC

One design concept for adequate wiring installation is based on the relationship of energy level and circuit impedance of a wire carrying desired information, to that of a wire carrying interfering energy. This will indicate whether the principal interference coupling medium may be a magnetic field or an electric field. The influence one wire exerts upon another is the vector sum of energies coupled by both the magnetic and the electric fields. This concept can be indicated in corollary terms by classifying wires according to their sensitivity to either inductive coupling or capacitive coupling. For example, inductive coupling (via magnetic fields) is the principal EMI coupling mechanism of low impedance circuits; capacitive coupling (via electric fields) is the principal EMI coupling mechanism of high impedance circuits.

A scheme for classifying aircraft wiring according to emission levels of wires capable of emitting EMI, and sensitivity levels of potential victim wires, has been promulgated by Mr. G. J. King of Douglas Aircraft Company (see Reference 8). Categories and descriptive characteristics are set forth in the following paragraphs. The proposed wiring categories apply to the wires themselves, rather than to the equipment classifications discussed elsewhere. A wire routing plan based on the described categories can be effective in minimizing intra-system EMI and may be effective in reducing filter requirements in user equipments.

Category I - Power Wiring - Cateogry I is comprised of the following:

1. Three phase distribution wiring (115/200 volts AC)
2. Single phase distribution wiring (115 volts AC)
3. Other wiring carrying 115 volts AC
4. Low voltage DC (28 volts or less) carrying more than 5 amperes

Two fields of coupled energy can cause interference: the magnetic field and the electric field. Of the two, the magnetic field is more difficult to handle because shielding at power frequencies requires heavy magnetic materials. One

method of magnetic field isolation is physical separation of the current-carrying wires from other wiring that is susceptible to magnetic coupling; another is the use of twisted pairs for power wiring. Power utilization devices such as motors, relays, most power transformers, acutators, and electric heaters are inherently insensitive to induced voltages, induced phase shift, and transients. Therefore, it is possible to group all distribution power lines into one category. Primary wiring or main feeders are excluded from such grouping to avoid unwanted surges if faults occur.

Category II - Secondary Power - Secondary power wiring is generally classed as power wiring at voltages less than 115 volts (AC or DC). EMI on secondary power wiring can be troublesome in restricted areas such as cockpits, radio racks, cable runs, and other areas requiring dense wiring. Secondary power lines are usually associated with interior lighting circuits, synchro circuits, small motors, and actuator circuits. Therefore, Category II includes:

1. Low-voltage power circuits (5 amperes or less)
2. Low-voltage lighting circuits (5 amperes or less)
3. Synchro and servo circuits not in Category III
4. Wiring from an equipment power supply or inverter to other equipments within the same system for DC voltages up to 5000 volts

Category III - Control Wiring - In discussing Category I, the coupling effects of the magnetic and electric fields were noted. In Category III, wiring is grouped according to the transient fields that exhibit both characteristics. Line transients occasioned by operation of equipments can produce transient magnetic fields associated with a fast rise time of the current. High voltage transients, caused by inductive kick-back can produce broadband RF voltages. Category III includes:

1. All wiring that involves the operation of relays, solenoids, stepper switches, automatic homing switches, and intermittent pulsing energy
2. Any other wire that can produce pulse energy caused by operating characteristics of the system or equipment such as wiring to flashing incandescent or gaseous strobe exterior lights

Category IV - Sensitive Wiring - There are many wires within a system under this category. High impedance wiring in this category is susceptible to electric fields of energy and low impedance circuits are susceptible to magnetic fields. However, a low impedance circuit can conduct capacitively coupled extraneous energy directly into a sensitive circuit such as a microphone input to an amplifier. Dual protection is usually required for these circuits.

Category IV includes:

1. Microphone circuits that invariably require twisted shielded leads to reduce coupled magnetic and electric fields
2. Audio output and video circuits
3. Sensitivity control circuits and volume or gain controls

4. Cathode and grid circuits, and FET or SCR gate circuits
5. Signal wiring requiring a protective electromagnetic shield
6. Metering and bridge input circuits
7. Circuits associated with low level signal inputs to a computer
8. Signal circuits associated with a demodulator

Category IV wiring should generally be shielded.

Category V - Susceptible Wiring - Experience has shown that certain wiring is extremely susceptible to almost all levels of electrical energy. Such wiring will usually need to be routed free of all other wiring and should not be grouped into a bundle unless associated with a single system. Antenna cables may be grouped if the shielding of the entire system is good. High power antenna cables and pulse cables should not be grouped with susceptible wiring.

Category V includes:

1. Radio antenna coaxial cables
2. Wiring to electro-explosive devices
3. Shielded wires for the fire warning system
4. Fuel quantity coaxial cables
5. Liquid oxygen indicator coaxial cables
6. Other wiring pertaining to safety of flight items such as anti-skid systems and spoiler actuator circuits

From a practical standpoint, many coaxial cables in communications-navigation subsystems may be grouped together, not necessarily in the same bundle but within the confines of a 2" x 4" wireway, with no ill effects from EMI. In such an arrangement, the more sensitive cables can still be adequately isolated from the power transmitting cables. However, some subsystem cables should be separated from all others for safety of flight or system integrity, rather than for susceptibility considerations.

Category VI - System Wiring - Category VI is a compromise designed for convenience of installation. To minimize extensive separation of system wiring bundles and to reduce the resulting wiring complexity, certain system bundles may contain wiring that otherwise would appear in Categories II, III, and IV. Category VI does not contain wiring that is classed as Category I or V. System groups may be installed only after careful analysis has indicated that the system is free of self-induced interference. An example would be the automatic flight control system (AFCS) that is inherently susceptible. The AFCS usually has many interconnecting wires between multiple black boxes grouped in close proximity. These runs, and the long runs from the immediate area to the control center, are classified as Category VI. There may be more than one system within the complex that would be classified as Category VI. It is suggested that each system bundle be identified and routed separately. It is not recommended that bundles of Category VI wires be grouped together.

Design Limitations

To assure minimum coupling for the six categories described, the required

physical separation must be given in quantitive terms for the entire wire or cable run. Where space is available, maximum separation between power system wiring and electronic system wiring should be maintained. Sometimes this can be done by routing power wiring on one side of the aircraft and electronics subsystems wiring on the other. Main power feeders should also be routed separately from all other wiring and located as close to the aircraft structure as possible. When routing wiring in areas where space does not permit greater separation, use the values in Table 16-1.

CATEGORY	DESCRIPTION	SEPARATION (INCHES)
I	PRIMARY FEEDERS	12
	DISTRIBUTION WIRING	6
II	SECONDARY POWER	3
III	CONTROL WIRING	3
IV	SENSITIVE WIRING	3
V	SUSCEPTIBLE WIRING	3
VI	SYSTEM WIRING	3 (INCLUDING OTHER VI'S)

TABLE 16-1 MINIMUM SEPARATION DISTANCES (INCHES) BETWEEN CATEGORIES

Installation Consideration

Structural arrangements and design considerations may preclude holding to criteria of minimum separation distances. Optimum arrangements and routing treatments can be established, however, such as suggested in the following:

Lightening Holes - Wire bundles should not exceed the limits of minimum spacing unless it is necessary to route them through the same lightening hole. They should splay away upon exit, or as soon thereafter as possible. Normally, there are no restrictions on the category of bundles in such an arrangement. It is preferred, however, to route Categories IV, V and VI through adjacent holes wherever possible.

The categories to be routed through adjacent holes may depend upon the physical size of such bundles. See Figure 16-1. An actual cable installation in a

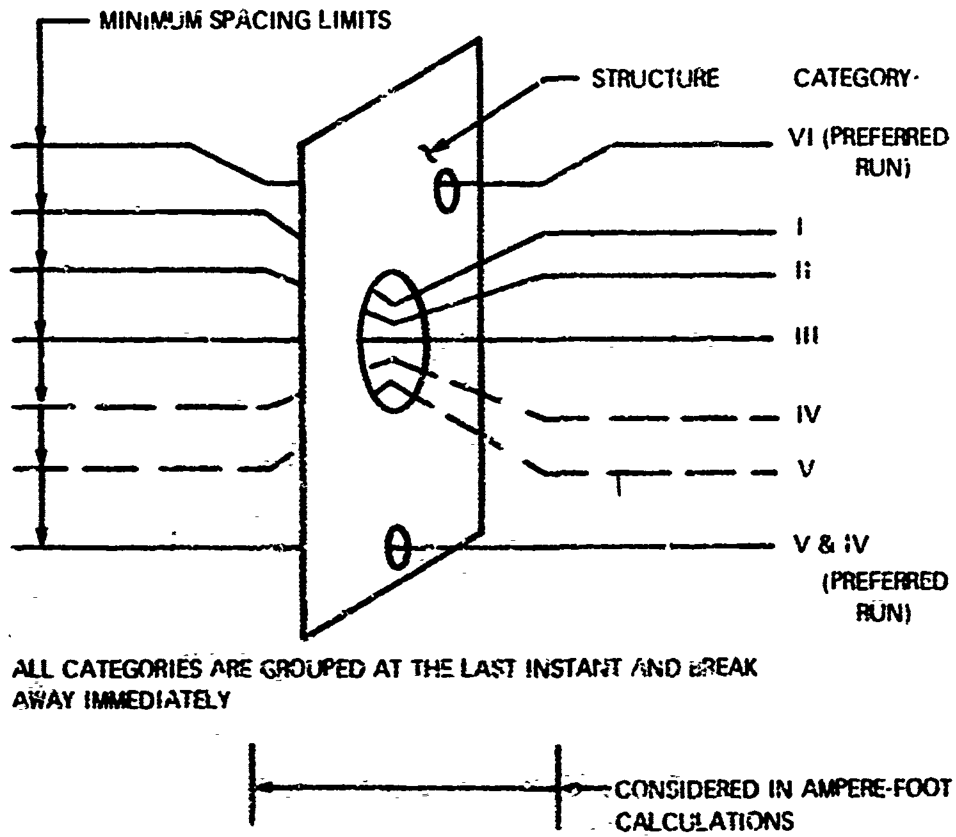


FIGURE 16-1 EXAMPLE OF CATEGORIZED WIRES GROUPED AT A LIGHTENING HOLE

helicopter is shown in Figure 16-1A. The cables are dressed apart on each side of each lightening hole.

Common Plugs - Usage of common equipment and bulkhead plugs should be treated in the same manner as lightening holes. Wiring should be segregated into categories. See Figures 16-2 and 16-3.

If EMC considerations are designed into the system from conception, common plug problems will be minimized when bundles are grouped according to sensitivity category and are manufactured to extend plug-to-plug from one end of the bundle to the other. Modern techniques using molded cable harnesses or flat wiring lend themselves readily to such measures. With system integration of wiring, separation between power and sensitive wires can be maintained.

Conduit - Grouping of wires in conduit will usually be similar to grouping used for wire bundles. Non-metallic conduit is preferred for reasons of weight. Metallic conduit may be used to increase isolation when conduits are closely nested and to take advantage of shielding effects. Aluminum conduit should be used for electrostatic shielding, and special purpose steels for magnetic shielding. Unrestricted use of metallic conduit should be discouraged, however, since

FIGURE 16-1A CABLE DRESS THROUGH LIGHTENING HOLES

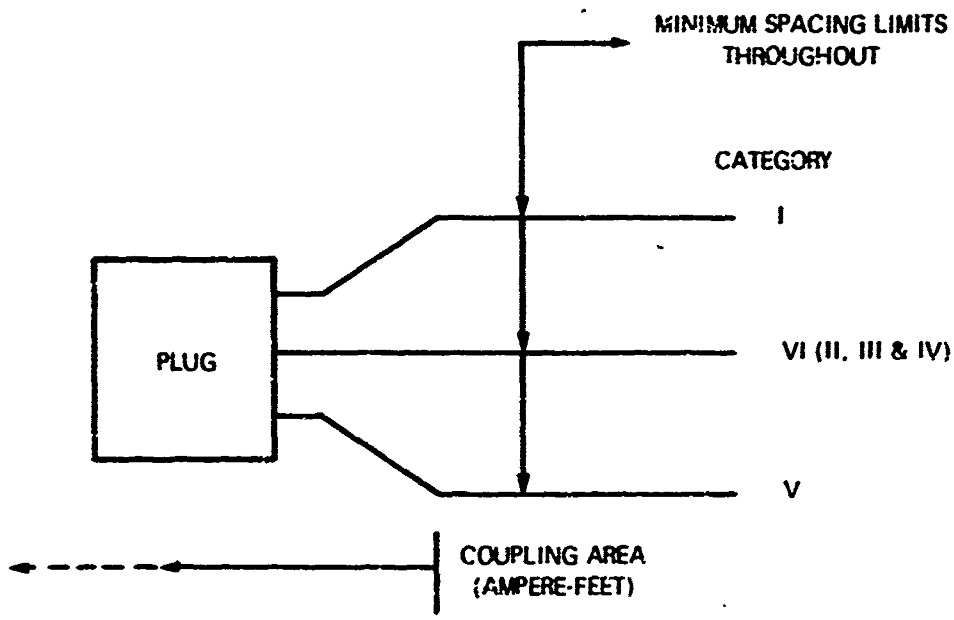


FIGURE 16-2 EXAMPLE OF CATEGORY VI WIRES GROUPED AT A COMMON PLUG

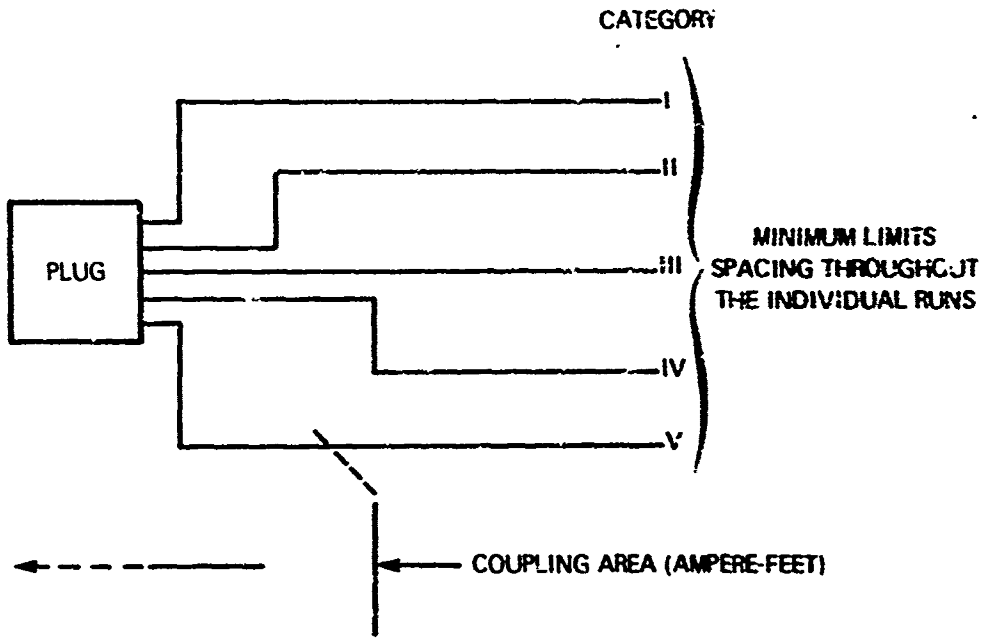


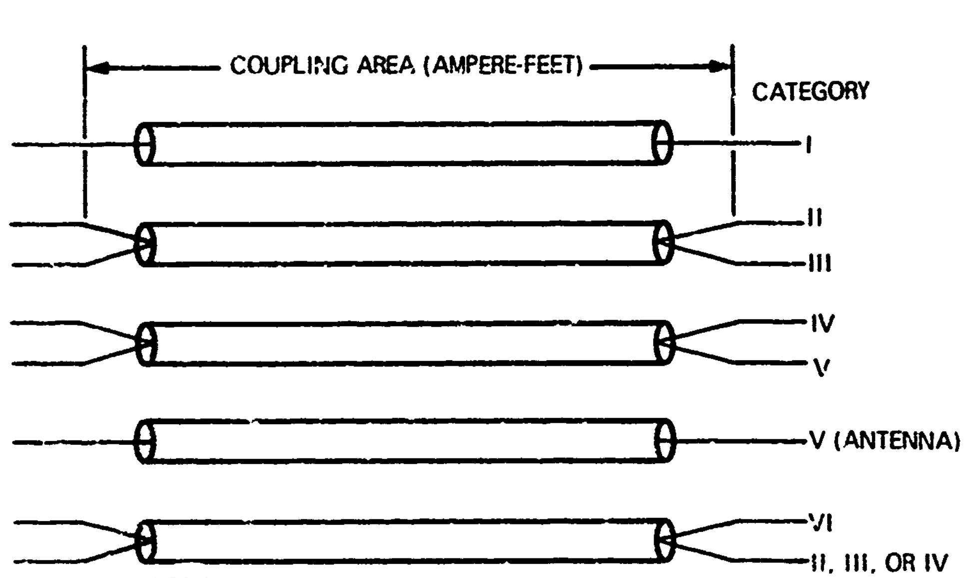
FIGURE 16-3 EXAMPLE OF CATEGORIZED WIRES GROUPED AT A COMMON PLUG

reflected inner fields can increase coupling between wires within the conduit (Figure 16-4).

Practical considerations for installation of bundles require adherence to certain basic rules, and deviation should be held to an absolute minimum. There will be areas where spacing between bundles will be less than the desired minimum distance. Other areas may require that wires originating at an equipment plug be bundled together for a specified distance. Installation designers will have to control such wiring arrangement design to ensure that compromised areas do not result in an unbalance favoring interference. What is lost on one end of the scale must be regained at the other.

For example, minimum design spacing requirements may have to be relaxed in close areas such as cockpits and control centers. This could be justified by achieving optimum separation in the rest of the aircraft, resulting in effective coupling far below threshold sensitivity. The following categories may be grouped together in particularly congested areas:

1. II with III
2. IV with V
3. VI with II, III, or IV



NOTES:

1. METALLIC CONDUIT MAY BE USED TO ACHIEVE ISOLATION EFFECTS WHEN MINIMUM SPACING CANNOT BE OBTAINED.
2. DO NOT USE LONG RUNS OF METALLIC CONDUIT FOR CATAGORIES IV, V, AND VI. (THIS WOULD CAUSE CLOSER COUPLING OF THE ENCLOSED WIRES BECAUSE OF REFLECTION EFFECTS.)
3. STEEL (HIGH MU) CONDUIT MAY BE USED FOR INCREASED ISOLATION FOR CATEGORIES I, II, AND III.

FIGURE 16-4 GROUPING OF CATEGORIES THROUGH CONDUIT

Under these circumstances, it is not recommended that Category I wiring be bundled with any other category or group. Maximum distance should be provided between Category I and Categories IV and V, even in such situations.

Special Wiring - Special wiring includes all wiring configurations other than single-conductor-insulated wire. Special wires are always used for control of interference, and, in wire categorization, they are used to isolate where minimum physical distances must be reduced for practical reasons. Therefore, special wiring would replace single conductor wire under certain installation conditions. Special wiring should definitely be identified in system design drawings to control and optimize its use. Special wiring may include magnetically shielded wire as well as electrostatically shielded wire.

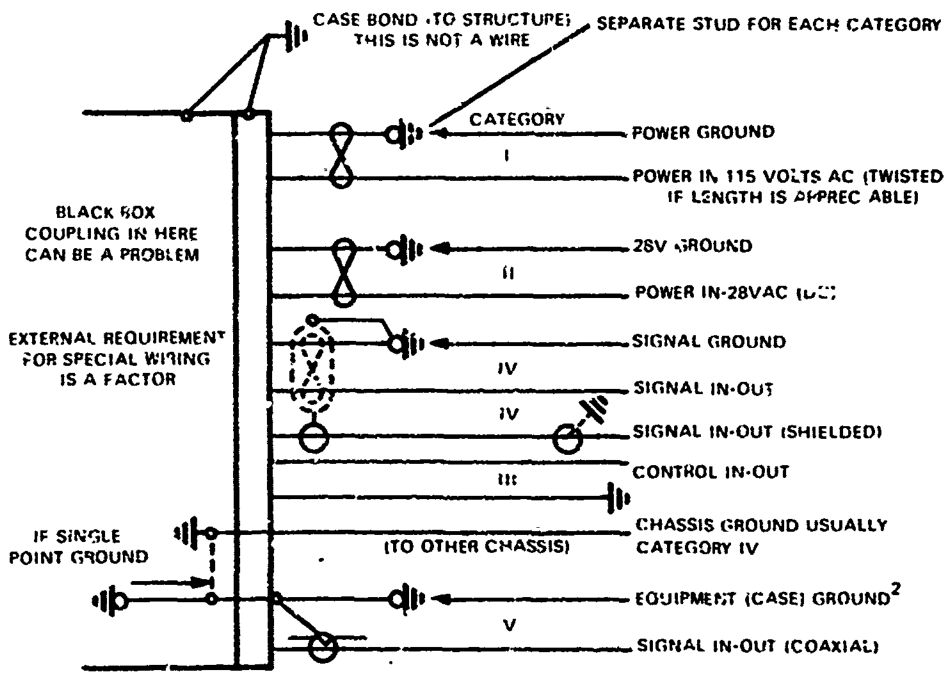
There are two types of special wire: twisted wires with two or more conductors and shielded conductors with one or more shields. Twisted wires are used for control of radiated or induced magnetic fields, and shielded wire is used for containment or exclusion of electric fields. Combinations of both are used where the circuitry may be susceptible to magnetic and electric fields. Recommended configurations include the following: twisted pairs, shielded twisted pairs, shielded single conductor, and various configurations of coaxial cable.

Figure 16-4A shows special wiring in the tailboom of a helicopter. The communication and control wires are separated into groups, each of which includes wires that are unshielded, shielded, and twisted and shielded. These groups are separated from the coaxial cables, which are separated according to individual requirements based on sensitivity and power level.

Special wiring is used only when necessary as called out in the system design. Requirements for use of special wiring may be reduced by considering the environmental effects before the electrical/electronics portion of the system is designed. Unrestricted use of shielded wire can produce problems as well as solve them. The unrestricted use of twisted wiring is discouraged because of the increased cross sectional area and weight. Under the categorization rules, special wiring is used only where design separation distances cannot be achieved.

Special Wiring and Pigtails - Electronic and electrical equipment racks are frequently so congested that wire separation to design limits is impossible. The problem can be resolved by considering as a pigtail, all wires from the point where they are attached to a single equipment connector to the point where they break into categories at a distribution center or a terminal board. Pigtail length can vary from two to ten feet. Lengths of more than ten feet should be considered for classification into categories. Since space isolation is not possible in a pigtail, the only recourse is to specify the use of special wiring (Figure 16-5) Power wiring should be twisted with the ground return for wires grouped under Categories I and II. Single conductor signal wiring (Categories IV and V) should be shielded. Two-conductor signal wirings (Categories IV and V) such as microphone circuits, should be twisted and shielded. Category II, other than power wiring, and Category III do not require special wiring. After the wiring has entered the proper categories, special wiring is not generally needed to achieve isolation in a pigtail. Figure 16-6 is a description of an equipment rack

FIGURE 16-4A WIRING INSTALLATION IN TAILBOOM



NOTES:

1. SHIELD GROUND POINT DEPENDS UPON LOCATION OF MATING GROUND AND WHETHER SHIELD-IN OR SHIELD OUT TECHNIQUES BEING USED.

2. USUALLY WILL TAKE CATEGORY I DESIGNATION.

FIGURE 16-5 GROUNDING TECHNIQUES FOR SPECIAL WIRING

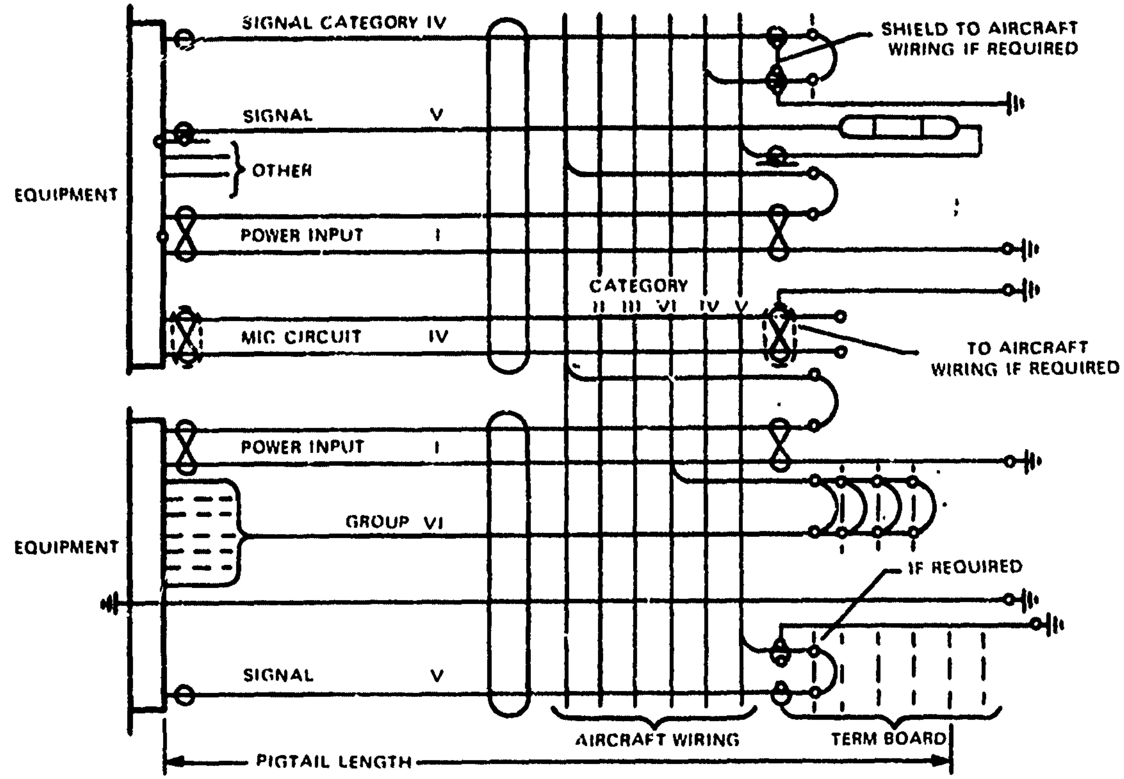


FIGURE 16-6 SPECIAL WIRING REQUIREMENTS FOR EQUIPMENT PIGTAILS

using pigtails from the equipment plugs to the terminal junction and then to the categorized aircraft wiring.

Figure 16-6 shows the categorized wiring labeled in a definite order. When using parallel runs, where all of the categories are in the same plane, it is desirable to locate the bundles for minimum coupling. The suggested order would be: I, II, III, VI, IV and V where Category I is always farthest from any terminal board wiring and Categories IV and V.

Ground Wires - Ground wires should always be grouped with their comparable supply wires. Twisting of pairs of wires always refers to the supply wire and its return, which may be ground. Twisted pairs of wires may be used either on circuits of transmission (Categories I, II and III) or circuits of reception (Categories IV and V). The former reduces the magnetic field coincident with current flow and the latter inhibits induced magnetic fields. Twisted wires may also be used to reduce the loop aperture where a tight twist results in minimum loop area.

Ground Studs - All ground studs will take on the category of the attaching wire. Thus only one category can be connected to a given ground stud. The ground stud must exhibit low impedance to ground to preclude common mode coupling.

Conclusions

Application of a classification plan to all aircraft wiring will considerably reduce system interference caused by inadvertent wire coupling. If the wiring plan is known to be effective, interferences mistakenly laid to wire coupling may be resolved as system deficiencies.

Wire classification is a distinct aid to tracking down and solving many EMI problems. The classification plan does not conflict with circuit or interconnecting wiring design; it is merely a specific installation procedure. Preparation of drawings that apply a part number to the wiring are not affected by wire classification requirements. Changes to equipment allowances of an existing aircraft may present a new set of problems. Economically, the costs of engineering design are more than offset by the small amount of rework for a given production design. Wire classification eliminates the wide variance in compatibility found on aircraft that contain random wiring installation.

REVIEW OF MIL-W-5088C

Specification MIL-W-5088C with Interim Amendment 1, dated 3 September 1968, covers the installation of wiring and wiring devices used for interconnection of electric and electronic equipment in aircraft. It applies to both AC and DC power wiring as well as to electronic wiring. The purpose of the specification is primarily to provide rules for installation of aircraft wiring. Because the wiring installation has a profound effect on interference control in an aircraft, it should be considered as an aircraft subsystem in its own right and planning conducted accordingly.

All MIL-W-5088C requirements are not of equal importance from the EMI point of view, and some requirements have only an indirect relationship to EMI. For instance, the requirements for materials covered in paragraph 3.4 are especially important to EMI. It is concerned with problems caused by the materials themselves in making electrical connections in the aircraft wiring. Generally, metals used must be corrosion-resistant or protected to resist corrosion and electrolytic action during the service life of the equipment or subsystem. This requirement is imposed to ensure that electrical connections will be of low resistance and not nonlinear junction rectifier sources of EMI. When metals corrode or electrolytic action occurs, resistance of electrical connections may change. Junctions having appreciable nonlinear resistance may develop, which in turn may also support intermodulation of signals. If the rules for joining dissimilar metals are not followed, serious electrolytic action can occur. This situation may create an EMI problem, or the actual connection may be destroyed and the electrical connection may fail. Other aspects of MIL-W-5088C paragraph 3.4 that relate to insulation materials and non-metals are not of critical interest from the EMI viewpoint, but adherence is a requirement since non-metals and insulating materials may form conducting paths for unwanted currents that could develop into sources of EMI. Consequently, the provisions of paragraph 3.4 must be followed to assure that EMI sources do not develop due to materials used in making electrical connections.

The requirements of MIL-W-5088C paragraph 3.8 are of particular importance to the EMI aspects of any aircraft installation. This paragraph is concerned with ground returns of aircraft wiring and specifies that the primary reference ground of the electrical system shall be the aircraft structure itself. A major consideration is that the ground connection must be free of corrosion problems. If a ground connection is subject to corrosion, its effectiveness as a ground is destroyed. Paragraph 3.8 specifically requires that ground return electric wiring not be connected directly to magnesium parts because of potentially severe electrolytic action and consequent degradation of the grounding system.

Two special aspects of paragraph 3.8 should be noted. The first concerns a requirement that shielded wires for HF circuits, have a shield connected to the prime reference ground (aircraft structure) at each end. Shielding grounds must provide an equipotential path throughout the entire run of the shielded wire.

The second special aspect of paragraph 3.8 is concerned with multiple grounds. No more than four ground leads shall be connected to a common ground stud. Separation of power sources should be assured by providing each power source with a separate ground connection to the aircraft structure. Grounds for equipments may be connected to common ground points only when supplied by the same power source. This arrangement will help to prevent interaction between electric systems of different characteristics if a common point should become disconnected from ground.

The requirements of MIL-W-5088C paragraph 3.9 are mostly concerned with selection of particular kinds of cable and requirements for procurement application. The most important feature from an EMI viewpoint is that the wire

and cabling should have sufficient current-carrying capacity and that voltage drops should be within limits to provide satisfactory operation of equipment. Tables in MIL-W-5088C give specifications that must be adhered to for current-carrying capacity of wires and cables. The other important consideration of this paragraph is contained in the sub-paragraph "Wires and Cables in Bundles." It states that current ratings for wires and cables given in the table are based on bundles of 15 or more wires and cables carrying no more than 20 percent of the total carrying capacity of the bundle. From the EMI viewpoint, the important consideration is how these bundles are made up. Bundling of cables can become rather complex depending on the system in question.

EMI problems relating to wires become more critical as systems grow in size. Interference problems from wiring in small systems can be minimized in many cases by not bundling wires and by using certain geometric configurations. As systems increase in size, wires must be bundled or grouped together. Bundling and grouping must be done carefully to assure that necessary isolation is achieved. Wires and cables should be grouped to isolate low, medium, and high level circuits from each other. According to the generally accepted definition for DoD contractors, low level circuits are those that carry less than 1000 microvolt signals; medium level circuits carry between 1000 microvolts and 3-5 volts; high level circuits are all AC prime power and radar pulse circuits. If these various circuits are grouped according to signal level, further benefits may be attained by shielding each group from the others by a variety of means. Shields such as wireways are especially effective if they are connected to ground by a low impedance path. This is easily accomplished on most airplane installations since the airplane structure and the wireways can be easily bonded together. Bonding is necessary because the wireways may be electrically isolated from one another even though they are part of the aircraft structure. This method will assure a degree of shielding that may substantially reduce interference between circuit groups.

In MIL-W-5088C paragraph 3.10.2, "Installation," some aspects of electrical installation related to EMI are covered in a general manner. The key to this paragraph and its sub-headings is that there must be, in every installation, good sound electrical connections, properly spaced, with accessibility for inspection and maintenance and adequate separation of circuitry to assure that sensitive circuitry is protected against potential interference.

Details given in these paragraphs are essentially qualitative but they can be quantized for specific installations by stating minimum acceptable impedance measurements of any junction, signal, or ground; by stating actual measurable separation distance between circuitry; and by giving actual worst-case limits to detrimental leakage currents between circuits. The matter of accessibility is not within the scope of this EMI publication. However, the interrelation between EMI requirements and maintenance requirements must be considered in system planning. For example, low impedance path connections to primary grounds may be inspected and difficulties avoided rather than fixed after the fact.

MIL-W-5088C subparagraph 3.11.1 "Radio Interference" is specifically concerned with the EMI problem. The paragraph includes specific guidelines for

wire and cable routing. Consequently, the provisions of paragraph 3.11 must be adhered to in the various subparagraph details and item (b) under 3.11, "As a design objective, wiring shall be routed so as not to be a source of interference or coupling between systems." The detailed paragraphs merely list various types of wiring that must be separated from one another. For example, paragraph 3.11.1.1 "Communication" states, "Audio and similar wires and cables of radio communication equipment shall be routed separately from cables of other equipment." The paragraph - "Antenna Cables" states, "Antenna cables shall be separated from any other antenna cable or cable group." Simple mechanical compliance with the provisions may not be sufficient to achieve the fundamental EMC objectives. The planning and prediction stages of system development should include an evaluation of projected wiring schemes to determine what features of the wire and cabling installation must be adapted to this end.

The final section of the specification, paragraph 6, entitled "Notes" includes a subparagraph entitled "Bonding," which states, "Bonding and ground returns should be installed in accordance with the latest version of MIL-B-5087." Bonding and grounding are discussed in more detail in another chapter.

EMI MINIMIZATION IN SYSTEM ELEMENTS

SUBSYSTEM PLANNING

To minimize EMI in a system or equipment, EMI must first be satisfactorily controlled and reduced in the various individual circuits. This calls for detailed consideration of the electromagnetic characteristics of functional circuits, of the parts that make up these circuits, and of the interrelationships of the parts and their circuitry. The aircraft subsystems and systems must be analyzed for effectiveness of grounding, shielding, bonding, and filtering that make EMI control possible. Analysis involves all elements of the system engineering discipline, with particular emphasis on how the system is analyzed, how to predict system performance, and what elements are involved in trade-offs. The trade-offs must include all elements essential to system performance, they must be representative of typical operational modes, they must be given suitable weighting, and finally, they must be incorporated into a mathematical relationship that permits rapid determination of the results of introducing various alternatives.

While electromagnetic compatibility is of great importance because it contributes to overall system performance, it is not the sole consideration. Total system effectiveness depends upon many other factors, including probability of survival and operational availability. Attempts have been made to relate systems effectiveness to EMC, but so far no substantial techniques have been developed to make a solid determination of this. Therefore, in planning a design for minimizing interference in a system or equipment, the trade-off analysis should

be explored to the fullest and the result will be a system or equipment with fewer design deficiencies requiring remedial action.

SYSTEM ANALYSIS

A system analysis to determine compatibility will include a compilation of interference sources, interference victims, and the possible coupling between members of these two groups. The source victim groups belong to two domains: the domain of the system under evaluation and the domain outside of this system.

It is usually initially established that electromagnetic compatibility of the system domain with the outside domain will put design constraints on the system. These constraints are determined by existing interference levels and susceptibility thresholds before introduction of the new system into its frequency location in the real world. These constraints, in the form of EMI limits and susceptibility thresholds, are usually requirements imposed by the aircraft mission during pre-flight, flight, and post-flight phases. For example, the flight phase of an aircraft used for ASW is different from that of an observation aircraft. Each subphase of a mission must be examined to insure that it is fully considered regarding its possible contribtuion to EMI problems. Assessment must be made of all intra-relationships of a particular system along with interface relations with any and all other systems.

In the domain of the system, analysis deals with the characteristics of the interference-producing devices and the devices that are potential victims of interference. Ideally, these two kinds of devices must function operationally while co-existing in complete compatibility. They must also meet specified weight and space limitations. Analysis must consider all modes of coupling in and out of these devices. Where the analysis indicated a condition of incompatibility, controls and specifications to achieve EMC may have to be developed.

Source of Interference

Once the overall background electromagnetic environment level and sources have been identified, the influence of these sources on the proposed system must be determined. Potentially interfering signals must be traced from their source to susceptible areas. The electromagnetic environment must be identified and described for potential problem areas. Such a description should include the characteristics of the environmental energy and discrete signals. It may be tabulated or listed by automation complex systems. Key characteristics such as signal levels, modulation characteristics, and processing methods should be listed as they appear as potential or actual inputs to susceptible devices. ECAC support the DoD EMC program by maintaining environmental data files on possible sources of EMI.

The final stage of analysis determines allowable limits of susceptibility of particular items within the portion of the system being analyzed. Match and comparison techniques can be applied to susceptibility characteristics with

calculations to pinpoint potential EMC problem areas. Such an approach concerns itself only with the most important equipments and thereby minimizes the number of equipments that must be considered. Sources that produce potentially large interfering signals relative to the ambient environment are considered; all other signals are considered to be part of the overall background electromagnetic environment or ambient noise level present as a result of contributions from the vast number of electromagnetic energy sources.

Analysis of Problem Areas

The choice of sources to be individually analyzed or to be considered as part of the ambient electromagnetic background is of considerable importance. The task can be made simple by selecting the most obvious offenders for analysis and then assuming everything else is background. This approach is usually too gross, however, upon which to form an accurate analysis. It may result in an analysis that does not confront the serious offender sources not apparent at first glance. Nevertheless, this is the first trade-off that should be made. Interference analysis should be performed as part of a repititious process. It may begin by selecting the most obvious sources as worthy of detailed analysis. It may also involve expanding the number of sources under consideration so that all elements that do affect the system performance will be subjected to detailed analysis.

When a large system is under consideration, the repetitive process will necessarily be more extensive but a more refined analysis will emerge. Once the less susceptible equipments have been eliminated by initial analysis based on gross upper estimates, a more detailed analysis can be performed on the remaining susceptible equipments to determine whether they are being subjected to interference.

In most sensitive areas of EMI, there is usually close coupling between sources and receptors. Even relatively low level sources of EMI are therefore important. Careful consideration must be given to both functional and incidental sources for such items as transmitters, pulse modulators, sweep circuits, video pulses, synchronizer trigger pulses, thyratron or gas tubes, switching circuits, local oscillators, and multiplier or mixer circuits.

It is usually not necessary to give individual consideration to the large number of relatively low-level incidental and functional sources that were included in the sensitive areas. However, it will probably be necessary to consider fundamental and spurious outputs of all except the lowest level transmitters and incidental interference from sources that involve relatively large amounts of electrical power. For the less sensitive areas, there is usually so much less coupling involved that it is necessary to consider only high-power sources. Incidental sources of interference or spurious outputs of transmitters are of little interest. The frequency domain characteristics of the interference sources must now be specified. If this information is available as amplitude versus time it must be transformed into amplitude versus frequency. Usually this information can be obtained from the input and output waveforms of the particular device.

Sometimes, if such information is not available, measurements will have to be made to give information about these characteristics. From these two pieces of information, a good idea of the interference characteristics can be obtained.

The equipment must now be considered in terms of its operating environment. An equipment should respond only to the wanted signal, but equipments designed to respond to a particular signal are also likely to respond to unwanted signals that are large enough, or happen to produce a spurious response, or enter through an unintentional path.

System analysis can now proceed to evaluate the susceptibility of these equipments. The types of signals must be established and susceptibility versus frequency defined. Information must be obtained from performance specifications or from results of interference measurements made on the equipment. Because conduction is a common means by which unwanted signals get into a device, careful attention must be given to interconnection and cabling techniques.

Schematic and wiring diagrams must be studies to determine whether there is a direct path from an interference source to a susceptible equipment. A common power supply is a principal offender in such instances. Cable routing methods must be reviewed to determine whether they can cause coupling. Mechanical layout and assembly drawings must be reviewed to determine how much inherent shielding is provided by the system. This is usually provided by parts of the airplane structure or equipment cabinets or some structural support.

Then, consideration must be given to unwanted signals which get into a device by radiation. Propagation losses along the transmission path must be computed. Propagation loss calculations must consider the propagation mode, including, line-of-sight, diffraction, and surface wave; the site considerations; the frequency; the antenna characteristics; and the distance between the source and the susceptible equipment.

Compatibility can now be evaluated using this data. The key is to identify electromagnetic incompatibilities before problems arise. One starts by establishing the source function. The effect of the transmission path is then used to modify this source function to find the actual level at the susceptible device. This method applies whether the transmission path is a conduction path or a radiation path. The actual level at the susceptible device is the primary concern because this is the unwanted interfering signal level that must be controlled. A graph can be made of the source function that will give the power output in dBm for each frequency from the fundamental to the highest troublesome harmonic. Another plot can be made of transmission losses as a function of frequency. From these and the susceptibility response characteristics of the susceptible device in dBm, it can be ascertained which frequencies will have an amplitude large enough to be troublesome at the victim receiver. These frequencies are the ones that require suppression if system compatibility is to be achieved. Frequencies that do not cause unacceptable receiver responses can be considered compatible.

The only remaining aspect to be considered is whether the electromagnetic environment in which the equipment is operating has a deleterious effect on the

susceptible device. Self-generated degradation within the system will be further affected by interference entering through conduction or radiation. The combination of the two may cause perturbations in excess of the permissible susceptibility function. For example, if the third harmonic of the wanted frequency in a servo amplifier has an amplitude of x, and the conducted or radiated interference at the same frequency has an amplitude of y, a problem will be created. Because x and y are additive vectorially, their total value may not be permissible within the constraints of the susceptibility function.

We shall now see how one can go about defining the amount of reduction of unwanted signal needed to alleviate the problems and to discuss techniques for doing so.

System Design Control and EMI Reduction Methods

The preceding paragraph has indicated the methods for determining, by analysis, the most probable areas in which problems may occur. Once there is reasonable identification of these areas, EMI control and reduction are possible provided one is aware of the available techniques. These techniques differ depending on the stage of the program under consideration. These stages can be separated roughly as follows:

Phase 1 - Formulation of system concepts and specification of system parameters

Phase 2 - Selection or design of equipment to perform the functions specified in the system configuration of phase 1

Phase 3 - Tests and measurements in support of design

Phase 4 - Integration and tests of the system to assure compatibility

Basic considerations are unique to each phase. In Phase 1, such items as frequency allocations and assignments, transmitter power levels, receiver sensitivity levels, types and characteristics of modulation, and switching levels of digital circuits must be considered.

In Phases 2, and 3 equipments or design of the equipment that will be used in the system must be selected. It is necessary to consider EMC qualification when specifying equipment parameters, when testing equipments to ensure that they conform to specifications, and when planning installation or possible modification. Careful attention should be given to equipment interfacing. Qualification to EMC specifications can be achieved by proper circuit design, routing of cables, equipment packaging, filtering of input and output leads, shielding potential sources, and shielding sensitive equipments. Careful consideration should also be given to grounding and bonding procedures used in the system. A common ground plane for all components of the system should be provided and there should be assurances that components are electrically grounded and bonded.

Phase 4, which is concerned with integration and system testing, is an important phase since it is the final payoff. Properly selected EMC tests will uncover problems overlooked in the design process and the over-all system compatibility tests will ensure that the complete system performs properly and that the operation is not degraded by interference.

DESIGN TRADE-OFFS FOR INTERFERENCE REDUCTION

Trade-off Philosophy

All methods that have been discussed for control and reduction of interference must be considered with respect to cost, weight, production, schedules, reliability, maintainability, and other system parameters. Therefore, the basic philosophy to emerge is one of compromise. All operational requirements must be met and yet the system must be compatible within itself and with its environment. Consequently, there must be compromises to achieve the best system. For this, we introduce the notion of trade-offs. There are many factors involved, and these are interrelated in a complex fashion. These functions are dependent on each other, and certain factors must be maximized at the expense of others. These are complex and difficult relationships to define precisely. Judgment and experience play a very important role, and the more profound this judgment and experience, the better is the opportunity for success.

Many different trade-offs can be made, but to consider too many is just as dangerous as considering too few. Experience has shown that the most important categories to be considered in trade-offs are:

1. Operational Requirements - These are the basic requirements necessary for the system to perform its intended function. It is essential that operational requirements be fulfilled, but trade-off possibilities exist because there may be several different ways of satisfying a particular requirement. Sometimes an operational requirement will be the pacing factor in any trade-off. For example, if a secure system requires that no energy be allowed to permeate its ambient environment, there will be no possibility of trading-off this requirement against another.

2. Technical Parameters - These are the details that permit implementation of operational requirements. Usually there are many possibilities from which these parameters can be selected. They depend upon the use of existing equipment or upon completely new designs; they may depend upon certain modulation techniques or unique approaches to switching techniques. Obviously, this is a fertile area in which trade-offs may be performed.

3. Cost Parameters - These usually include other items besides those measured in terms of dollars. Certain related disciplines are covered under this category, because the method of selection has a big impact on cost. Reliability parameters are often best specified in terms of cost. A specific level of reliability will require a certain cost level: if reliability is increased, cost level will increase.

There are many opinions as to how much trade-off work can be done among the three preceding items. The lines of distinction are not clear-cut and sometimes an item in one category is really not too different from one in another category. For certain systems, cost is the key factor and practically no trade-offs can be done with it. Mission envelope requirements may be changed to accommodate the cost considerations. For example, with a cost fixed for communications equipment, there is very little opportunity to insist that the

airplane containing such an equipment satisfy a requirement for an 8-hour mission, when a 6-hour mission has the expected probability of success. The whole procedure of trade-off analysis is a subtle one and requires considerable skill to come up with an optimum system.

An example of a trade-off procedure can be given using a typical communication transmitter. Its operational requirements include a specific operating frequency and power level. The technical parameters require forced air cooling to keep the ambient temperature inside the equipment low enough to achieve reliability. To accomplish this, a rotary blower was decided upon, but the choice had to be made to use either a high-speed blower with a small space requirement or a different motor that required more space. A decision had to be made as to which penalty should be accepted. The high-speed motor required filters in its power leads to control the interference it created. This required additional space, and the particular power line filter capacitor would also have added to the interference. So a trade-off had to be made between the tolerable level of interference and the space requirement. It was found that by better packaging, more space was made available so that a high-speed motor was not required, and the interference created by the motor used was within tolerable limits.

Trade-off Relationships

Trade-off relationships are characterized by making do with less in a particular area so that an overall objective may be attained. For almost every positive step taken, a compensatory step must also be taken. The decision may be made to improve system compatibility by introducing shielding in a particular piece of equipment. Immediately, a number of negative compensatory factors are brought into play: the weight of the equipment increases; it becomes more costly; accessibility may be limited with an associated increased repair time; and ventilation may be obstructed, contributing to internal ambient temperature rise that will degrade reliability. The decision to go ahead with thin shielding depends on how many of these disadvantages can be lived with. The key consideration is to use only that degree of shielding necessary to assure EMC, and not go overboard so that undesirable factors outweigh the attainment of EMC.

The same parameters that produce the desired design performance characteristics may result in undesirable characteristics from the standpoint of electromagnetic interference. While nonlinear operation is undesirable from an interference standpoint because it produces a mechanism for the generation of harmonics and intermodulation products, in certain applications nonlinearities are used to obtain a desired characteristic. For example, a transmitter final power amplifier may be operated in a nonlinear manner to improve efficiency. The improved efficiency is at the cost of increased output of harmonics and unwanted intermodulation products. A basic trade-off must be made between increased efficiency and potential interference problems. The trade-off lies in determining which is the most desirable feature.

One of the most important electromagnetic compatibility considerations in the design of an electromagnetic system that generates or responds to a functional signal is the required bandwidth. If the bandwidth is made too wide, the transmitter frequency spectrum will occupy a large channel-width and the receiver will have a high noise figure and be vulnerable to adjacent-channel interference. If the bandwidth is made too narrow, system requirements such as frequency stability, signal quality, reliability, and redundancy may be so severe that they will be almost impossible to meet, and increased interference may result. So, to conserve spectrum space and yet control interference, such parameters as bandwidth, frequency accuracy, frequency stability, and selectivity requirements must undergo a trade-off review.

In establishing bandwidth requirements for pulse systems, careful consideration must be given to pulse shape. Fast rise time means broad frequency spectrum which in turn usually means interference problems. Therefore, modifying the pulse shape to eliminate the sharp rise time brings about a trade-off of resolution against system compatibility.

Abrupt changes in current waveforms, such as those that result from switching transients and synchronizer pulses, are generally undesirable as generators of interference. If possible, trade-offs should be made to eliminate switching transients and pulse-type signals. Sometimes it is possible to use a simpler interference-free design in place of a potential interference source.

Filters provide a very effective and widely used method for reducing or suppressing electromagnetic interference. Filters attenuate unwanted electromagnetic signals while passing wanted signals. Their use is particularly important in eliminating spurious outputs or responses that can cause an inter- or intra-system malfunction. The satisfactory use of a filter in a system requires careful consideration of a variety of trade-off factors such as the insertion loss, impedance, power handling capability, signal distortion, cost, weight, size, and its ability to reject unwanted signals.

A potential interference source of a susceptible equipment can be enclosed in a shield so that it cannot radiate or receive electromagnetic energy. In designing shields, trade-offs between shielding effectiveness and size, weight, cost, accessibility, and maintainability are important.

Trade-off Examples

A typical trade-off could be illustrated by considering communication between an airplane and a ground control station. Analysis of operational requirements indicates that an effective radiated power of 30 dBm is required to accomplish the objective.

The chosen effective radiated power (30 dBm or 1 watt) can be achieved through a variety of possible combinations of transmitter power and transmitting antenna gains. The range of possible antenna gains will vary from 0 dB to 20 dB. Therefore, on one extreme the operational requirement can be satisfied by using a transmitter with a power output of 30 dBm and an isotropic (0 dB) antenna. On the other extreme, the requirement can be satisfied by using

a transmitter with a power output of 10 dBm and an antenna gain of 20 dB. Between these two extremes, the operational requirements will be satisfied by any other combination of transmitter power outputs and antenna gains whose combined effective radiated power is 30 dBm.

The trade-off relationships must be examined to arrive at the best combination of transmitter power and antenna gains. For the sake of simplicity, consider that a major trade-off consideration in designing the particular onboard communication transmitter is weight. That is, the designer must select the combination of antenna gain and transmitter power that provides the minimum total weight.

Consider the curves shown in Figure 16-7. The two lower curves show the weights of the transmitter and its associated power supply, and the antenna and its associated hardware as a function of the power output and antenna gain respectively. From these curves, it is seen that, as expected, the weight of the transmitter and its power supply generally increase as the transmitter power is increased. Similarly, the antenna and its associated hardware also tend to increase in weight as the antenna gain is increased. The increase in total antenna weight with antenna gain will result partially from the degree of sophistication required to keep the antenna properly oriented as its pattern becomes more directional.

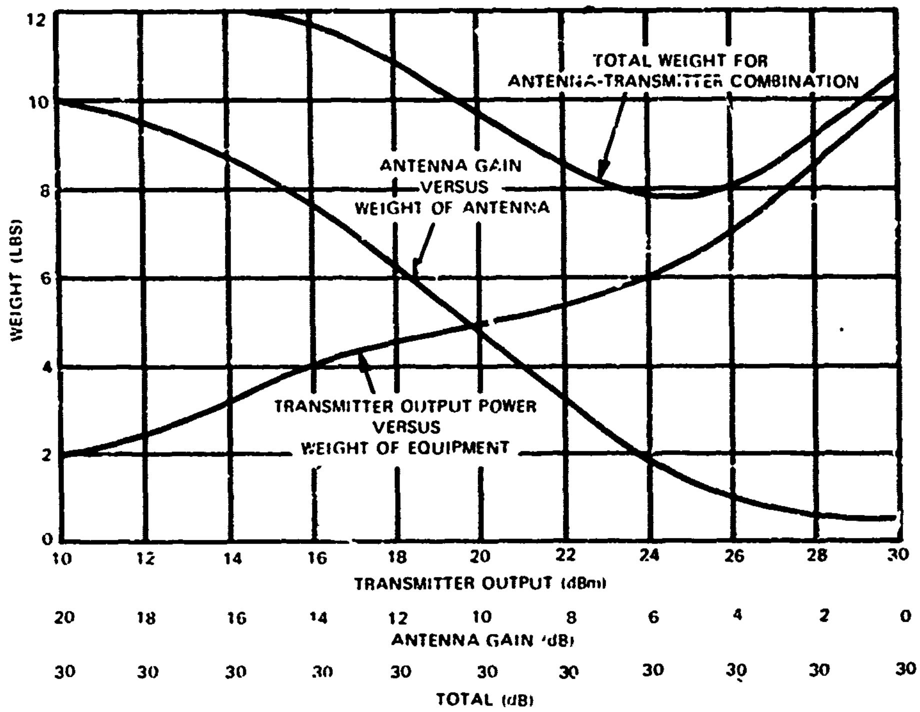


FIGURE 16-7 TRANSMITTER AND ANTENNA TRADE-OFFS

The upper curve in Figure 16-7 shows the total weight of the various transmitter power output and antenna gain combinations that will satisfy the 30 dBm requirement. From this curve, it is seen that there is a combination of transmitter power and antenna gain that will minimize total weight. This optimum combination occurs for transmitter outputs of 25 dBm and antenna gains of 5 dB. The resultant weight of 7.8 pound represents the minimum possible combined weight.

The trade-offs shown in Figure 16-7 illustrate how the designer would use trade-off concepts to arrive at an optimum system. However, the curves considered only the weight of the transmitter and antenna system and did not consider EMC. EMC considerations would be based upon a +25 dBm transmitter, and it may have been necessary to add some form of interference reduction to the transmitter to protect other onboard electronic equipments from spurious radiations. These interference reduction requirements would result in extra weight.

Therefore, to obtain a system compatible with the other onboard systems, the electromagnetic compatibility trade-off relationships must be included in the analysis, as shown in Figure 16-8. The lower three curves in this figure show the transmitter weight and the additional weight required to ensure compatibility as a function of transmitter power, and the antenna weight versus gain.

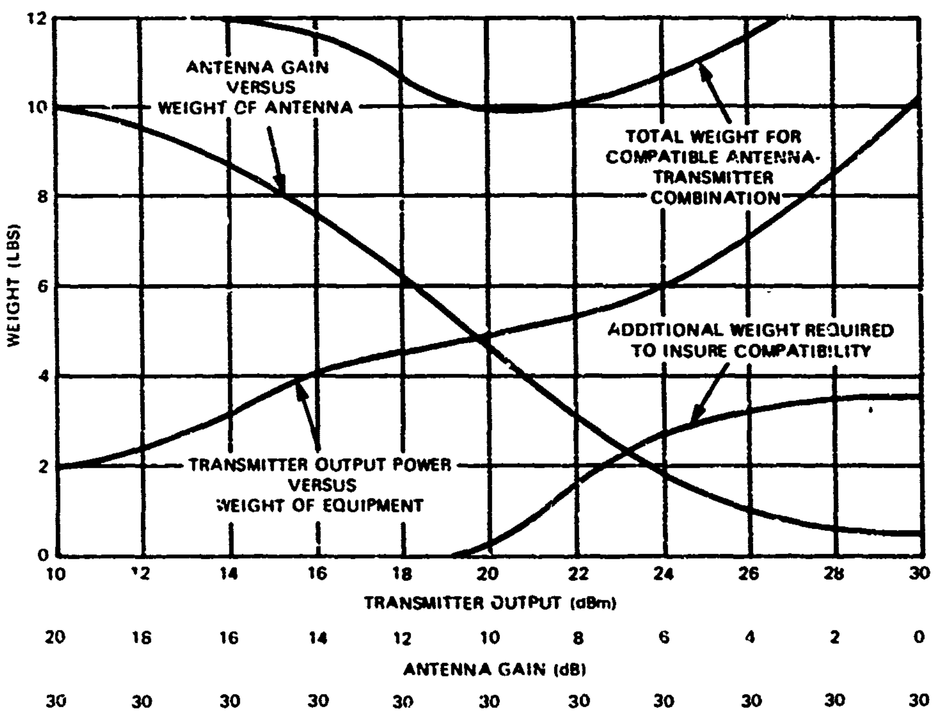


FIGURE 16-8 TRANSMITTER, ANTENNA, AND COMPATIBILITY TRADE-OFFS

The upper curve shows the total weight of the various transmitter power and antenna gain combinations with the additional requirements necessary to ensure compatibility. From this curve, it is seen that the minimum total weight for a compatible system is approximately ten pounds and occurs for a transmitter power output of 21 dBm and an antenna gain of 9 dB. If compatibility had not been considered, the resultant system might have required considerable additional weight to provide compatibility and the result would have been a less satisfactory system.

SYSTEM INTEGRATION AND EQUIPMENT INTERFACING EMI SUPPRESSION

The foregoing material has been concerned with EMI design and planning considerations applied to aircraft systems generally. It has been general in that the approach has been concerned with the principles involved rather than requirements of specific aircraft. Successful integration of individual subsystems in aircraft depends not only on adherence to these systems but also the practical considerations of how they are interconnected, how the system is configured, and how the basic grounding problem is handled.

Many different approaches can be taken using these principles and the exigencies of the particular installation. To illustrate these problems of integration, the Phantom jet fighter aircraft and the airborne warning and command aircraft were selected as examples of extreme complexity.

EMI CONTROL ANALYSIS OF SEVERAL TYPES OF AIRCRAFT

Phantom Jet Aircraft

The electromagnetic compatibility program for the Phantom aircraft had to solve a wide variety of interference problems. The aircraft involves high density installation of electronic, electrical, and electro-optical subsystems integrated to perform tactical reconnaissance. Early recognition of these potential electromagnetic interference problems resulted in a strict electromagnetic compatibility control program which included:

1. Equipment requirements
2. Design and development

Phase 1. included the basic contractual requirements of the procuring agency, and Phase 2. represents efforts that culminate in a design solution to these requirements. The requirements of MIL-I-26600 or MIL-I-6181D were imposed on all subsystems. Interface and interconnection aspects were continually assessed to achieve a high confidence level for weapon system compatibility.

Design and Development

All Phantom weapon system subcontractors were required to submit interference control plans. Careful control is exercised by the prime contractor

in cases where deviations are requested because of extreme costs or design compromise so that over-all system compatibility is not degraded. In some cases, preliminary reviews established design requirements exceeding existing electromagnetic compatibility and interference specifications. The prime contractor had the responsibility of anticipating these needs and directing attention to them as early as practical during design and development.

A critical factor often overlooked by many prime contractors is the usefulness of the subcontractor interference control plan. This was avoided by developing the vendor technical data requirements document. The EMI engineering group also assisted vendors by advising them of the intent and the detailed information that should be in an interference control plan. An Electromagnetic Interference Control Plan advises the procuring activity of the effort a vendor will make to preclude the possibility that his product will adversely affect, or be affected by, other equipments in close proximity to his installation. Adherence to this plan also assures that the vendor's product is unlikely to be affected by stray external interference signals from other equipments.

It was recommended that the following control plan topics be discussed by the vendor in as much detail as possible:

1. Circuits to be shielded
2. Circuits to be filtered
3. Method of selecting interference-free components
4. Methods of obtaining continuous shielding in equipment housing and enclosure, including access doors and other apertures
5. Definition of the frequency range for which the shielding is designed to keep interference signals from affecting vendor equipment, and the attenuation to be expected.
6. Protective finishes to be used on mating surfaces, and methods for maintaining good electrical conductivity when coatings are applied
7. Suggested methods of bonding shock mounted units to the aircraft structure
8. Methods for selecting ground points for circuits and suppression components to minimize stray coupling caused by common ground impedances and circulatory currents in the chassis
9. Precautions to be taken to prevent susceptibility, spurious emanations, responses, and unwanted resonances
10. Good engineering practices in suppression techniques, such as filtering, shielding, bonding, grounding, and isolation
11. Suppression measures that will be incorporated as an integral part of the vendor's system
12. Facilities available for testing to EMI specification and requirements
13. Administration of the vendor's EMI control plan, including:
    a. The number and qualifications of personnel assigned to the program
    b. The vendor's policy and the level of authority for influencing design to eliminate causes of interference

c. The vendor's designee for EMI liaison with the customer

Upon review of the vendor's control plan, the EMI control group can determine the areas that may present interference causing system incompatibility in the completed design. The EMI control group can then act to avert such interference by assisting the vendor in designing "fix" efforts or by providing for cable separation, shielding, or shading within the aircraft. Thus, the vendor's EMI control plan is a useful tool in the prime contractor's program for insuring that aircraft electromagnetic compatibility requirements can be met.

The plan is used to expose problems in advance, to eliminate or suppress them, and to provide further EMI liaison efforts with the vendor or between vendors and thereby to improve the product.

The prime contractor's interference control plan for the Phantom weapon system, which was a required contractual document submitted to the procurement activity, described a multi-phased program for analyzing, predicting, controlling, and monitoring potential audio and radio frequency interference within the aircraft to achieve electromagnetic compatibility of the weapon system.

The primary objective is that no undesirable response, malfunction, or degradation of performance due to electromagnetic interference occurs in or is produced by, electrical or electronic equipment installed in the Phantom. Performance criteria of this plan are maximum compatibility of systems and subsystems and overall system effectiveness obtained by interference design.

Installation Design Techniques

Special EMI-oriented design techniques were used to provide reasonable assurance that the requirements of the weapon system compatibility specification were achieved.

In early phases of weapon system design, there is relative freedom of choice of equipment, location, and cabling. Once the system is committed to a specific configuration, the level of electromagnetic interference has been essentially established and changes and improvements become difficult to make. The minimum change, minimum cost concept of the phantom aircraft made careful planning essential for optimum results in interference control. The initial work phase used all known system parameters in the following categories:

1. Susceptibilities and paths of entry of interference for each component of the aircraft system
2. Interference-producing capabilities of each component of the aircraft system
3. Limits on flexibility of component location and orientation imposed by structural and environmental considerations
4. Alternate antenna locations on the aircraft causing the least reduction in performance of installed equipments

Consideration was given to installation techniques of:

1. Physical isolation
2. Equipment grouping

3. Use of interference-reduction components
4. Structure shielding and shading
5. Equipment shielding
6. Airframe wiring and cabling

As are most complex weapon systems, the Phantom is an example of high density packaging. Physical isolation is difficult to achieve, as equipment grouping is dictated principally by mission requirements. Necessary suppression components were added later. Special shielding and shielding afforded by structure can be used only within limits of weight and practicality. Therefore, major installation considerations pursued were in equipment (case) shielding and in the heart of weapon system compatibility, aircraft interconnect wiring.

Since shielding for confinement of radio frequency energy is the most important element in reduction of radiated interference, vendor designs for equipment housing were carefully evaluated. An ideal shield has extremely high conductivity, great thickness, high permeability, and is virtually watertight, with no openings or discontinuities. Practical shields are usually compromises dictated by limits of weight and space.

The following design criteria were evaluated:

1. Thickness
2. Conductivity
3. Permeability
4. Minimum access openings
5. Joint construction

Equipment housing designs were reviewed to evaluate possible discontinuities in housing construction. The following considerations were applied: mechanical discontinuities were required to be minimum; joints and flat metal seams to be electrically continuous across the interface; and surfaces of joints to be mechanically smooth, highly conductive and noncorrosive, with joints welded wherever possible. Where bolts, rivets, or other fasteners were used, fastener spacing was made consistent with the amount of energy to be confined. Where bolts or screws were used, the necessity for RF gasketing or RF weather stripping was investigated. Bolts, screws, or any metal projections that passed through the equipment housing were particularly scrutinized for being RF tight.

Where relatively large holes for air flow were provided, the need for covering by well-bonded metallic tubing or conduit having the high-pass filter characteristics of a wave guide was evaluated.

Shock mounted chassis were bonded to the aircraft structure with bond straps no longer than five times their width, where practicable. Bond straps were specified to be accessible for maintenance.

Flexible conduit consists of metallic interlocking spiral hose with an outer covering of tightly woven metal braid. Without the outer braid, the flexible conduit offers good reflection, but is likely to leak at the junctions between spiral turns. This leakage can be quite serious at high frequencies. The outer braid reduces the leakage tendency. At low frequencies, the single braid outer covering yields about 50 dB more attenuation than does the flexible hose alone.

Due to space, weight, and maintenance considerations, the use of flexible conduit was avoided where possible; however, electromagnetic compatibility situations dictated its use in certain cases, and conduit recommended by military standard MIL-W-5088C was used.

Successful integration of individual subsystems in an aircraft weapons system depends to a great extent on the effects of interconnecting wiring and principles governing its grounding. In a small, dense complex aircraft like the Phantom, the possibility of inter- and intra-cable crosstalk among power, control, and signal circuits is high. In addition, irradiation of cables by high power CW and pulsed energy, with the possibility of high level coupling, may not only cause serious data degradation and system malfunction, but may also pose a threat of premature ignition of on-board ordnance devices.

The peculiarities of theories and principles of grounding interconnecting wiring make the problem more complex and often control the limiting factors in precluding malfunctions.

Major effort was directed toward electromagnetic compatibility of the aircraft system's electrical and electronic devices, equipments, and subsystems by giving careful attention to cable selection, routing, and related grounding. Extensive guidance was given to both prime and subcontractor engineering personnel in the use of proven techniques of interference control and to establish the aircraft interconnect design objectives. A unique aircraft wiring concept, the compact wire harness, posed additional problems in effecting required objectives.

To resolve the problems outlined above, close liaison was maintained with design engineers on each equipment, and the current, voltage, impedance, signal types, susceptibility, and sensitivity of each interconnect circuit were established. These data, combined with knowledge of lengths of interconnecting cables and equipment locations, provided information for an analysis of electrostatic and electromagnetic coupling. The results of the analysis were used in establishing effective, realistic EMI wiring criteria for new system installations in the Phantom aircraft. This coordination provided the guidance necessary in consideration of the aircraft interconnect installation.

Increasing complexities of electronic equipments and electrical wiring cause problems because of the increase in wiring and the smaller areas in which it must be placed. For example, the Phantom aircraft of 1964 had 18,000 feet of wire compared to 54,000 feet in today's Phantom II.

To solve a high density wiring problem, a program was established to investigate the state-of-the-art concepts and techniques for improving aircraft wire installations. From this program evolved a wiring method called the "compact wire harness." The compact wire harness, capable of withstanding 300°F for long periods of time, consists of a harness made–not from airframe wire, but from teflon-insulated hook-up wire designed for internal wiring of electrical and electronic equipments, and protected by a coated dacron braided outer cover. In addition to the approximate one-third decrease in the harness diameter, the compact wire harness is appreciably lighter, more flexible, more resistant to abrasion, has a better appearance, and cuts installation time in half

compared to conventional airframe wire harenesses.

In the initial cable analysis, it was evident that completely shielded wiring harness would be necessary. These needs were not severe enough to require flexible conduit, but dictated more stringent shielding than conventional shielded wiring afforded. This problem was investigated, with the following objectives:

1. To keep the harness diameter as small as possible and able to withstand 300°F without sacrificing performance or reliability
2. To determine the best method for providing a shield able to provide a minimum coverage of 85 percent as defined in MIL-C-27500
3. To obtain a good electrical bond between the shielding braid and the connector
4. To devise a method to feed a shielded harness through a potted pressure-sealed bushing
5. To fabricate a harness that could be repaired in the field

The investigation indicated that the best and easiest way to shield a harness was to fabricate the harness according to compact harness methods and braid tin-coated copper wire over it.

The first objective, that of keeping the bundle diameter to a minimum, was solved by fabrication of the bundle using the same basic methods used in the compact wire harness. This generally requires the use of MIL-E-16878, Type E, polytetrafluoroethylene insulated wire in place of airframe wire. While this wire lacks the physical properties of airframe wire, it has the same electrical properties. To provide the necessary protection from possible physical damage due to braiding of shielding over the wires, a heat-shrinkable polyolefin sleeving is applied over the bundle. Then after the shielding braid is applied, the harness is dacron braided and Kel-F coated.

The next objective, that of providing a shield medium over the harness, was solved by the use of braided tin-coated copper wire. This braid is applied by the use of a 24-carrier braiding machine equipped with an overhead sheave capstan. The machine, in general, is the type used in the manufacturing of shielded or coaxial cable. The machine permits the use of various sizes of braid wire, and by control of capstan speed and the number of wire ends per spool, one can obtain a minimum of 85 percent coverage as defined in MIL-D-27500 on bundles 1/4 to 1 inch in diameter.

The third objective, which was to obtain a good electrical bond between the shielding braid and the connector, was achieved by the use of a straight 90 degree strain relief clamp. Before the shield braiding is started, a metal sleeve is positioned on the harness under the clamp. This is done to prevent crushing the metal braid into the harness when the strain relief clamp is tightened on the braid. The process also provides a good mechanical and electrical bond between the shielding braid and the connector shell. A maximum bond resistance of 0.0025 ohms is required. In practice, the measured resistance is approximately 0.0001 ohm.

Fourth, the objective of devising a method to feed a shielded harness through a potted pressure sealed bushing was achieved by prepotting the wires

before braiding the metal. After the braiding is completed, the harness is again potted in the bushing.

The fifth objective, that of obtaining maximum shielding effectiveness for internal shielded and coaxial cables, was achieved by limiting the distance between the shield termination and the connector and by the use of a solder ring. Because of the limited space created by restricting the shield termination in the connector's strain relief clamp, a new polyolefin heat-shrinkable solder termination was used. This type of shield termination reduces the bundle diameter at terminations by approximately 20 per cent compared to other commonly known methods and allows the shield termination to be within 1/4 to 1 inch from the connector. These shields are then jumpered together by a solder ring consisting of a 16-gage noninsulated copper wire wrapped around the harness in the connector adapter. The shield jumpers are soldered to the solder ring and a ground lead is then attached to a connector contact and the solder ring; thus, the shields are grounded through the connector. To isolate these grounds from the bundle's external shielding, the connector's strain relief clamp is then potted. The primary purpose of potting is to waterproof the backside of the connector and to support the wires, but it also serves a secondary purpose, that of isolating the internal shields from external shields.

The last objective, to be able to repair the shielded bundle, has been restricted, but it can be done in a repair shop by personnel familiar with the harness and who have experience with the connector's strain relief clamp.

Additional evaluation work is required in the following areas:

1. Newer wire insulations for resistance to abrasion and cut-through to determine if insulation thickness can be reduced
2. Higher strength conductor to determine if the use of a smaller gage wire is feasible
3. Methods of lowering the density of potting compounds
4. Different materials to be used as a barrier between the wire and outer shield
5. Other methods and materials to provide an overall EMC shield and an abrasion-resistant covering for the harness
6. Better connector adapter to simplify repair of the harness

The objectives have been met to keep the harness diameter as small as possible without sacrificing reliability or performance, to maintain flexibility and decrease possible physical damage, and to provide a minimum shield coverage of 85 percent.

By meeting the above requirements, the use of flexible conduit has been limited to severe interference situations; maintainability and installation problems have been reduced; there have been weight reductions; and adequate shielding has been provided precluding the possibility of undesirable interference.

Electric and magnetic coupling analysis involved these factors: voltage, current, receiver circuit parallel impedance, receiving circuit sensitivity (voltage and waveform), length of cable run, and physical separation of source and

receiver wiring.

Equipment location had to be considered from the standpoint of flight missions of the aircraft, as well as the weight reduction that could be achieved from minimum cable lengths. This approach resulted in many potential coupling and cross-talk problems, since the designs of most equipments were not firm and therefore interconnect wiring characteristics were unknown. In some instances, highly susceptible cables had to be necessarily long and adjacent to "offenders," compounding interference problems. During electric and magnetic coupling analysis, cable lengths were considered but could not be changed. Cross-sectional area for cable routing was limited; this, coupled with the large number of interconnect cables, prevented wiring separation for a complete run. The above restrictions affected electrostatic coupling. Thus, if a wire length could have been decreased by a 10 to 1 factor, the voltage or current induced into the receiving wire would also have decreased by the same ratio, or 20 dB.

The alternatives remaining for EMI design engineering included interference control from the standpoints of impedances, circuit susceptibility, both level and waveform, and the generally accepted twisting and shielding of interconnect wiring. To provide a wiring configuration guideline, graphs were made that aided in the determination of coupling between source and receiver wiring. Extensive coordination permitted design changes that further precluded interference problems.

The grounding philosophy for use on the Phantom aircraft interconnecting wiring, as well as vendor equipment, was established after a careful review of the state-of-the-art objectives and available information concerning:

1. Transients
2. Ambient electromagnetic fields
3. Sensitivities
4. Cable pickup
5. Frequency data
6. Impedance data

The above review resulted in guidelines to be used by the EMI group in determining system grounding. The following rules were applied to the extent possible within the vendor's equipment as well as aircraft wiring:

1. Signal ground is the low side of circuits whose susceptibility characteristics are best described as low level, less than one volt, and low frequency, up to and including the high audio frequency range. The grounding technique used on the Phantom aircraft for signal ground was a modified single point ground in that no single point within the aircraft was used for signal ground, but rather each subsystem or black box contained its own signal ground that in turn was tied to aircraft ground as close as possible to its point of emerging from the subsystem. Transformers and other isolation devices were used to the extent possible to decrease the length of run necessary for each signal ground.

2. Signal shield ground refers to the ground, to aircraft structure, used for shields covering wires that are susceptible to low-level, low-frequency pickup. Frequency signal shields of less than 20 kHz are grounded at one end only.

3. RF interference shield ground refers to the ground of shields used to protect leads susceptible to RF fields or carrying RF energy. RF interference shields are grounded to the aircraft structure at both ends and at all breaks in the run.

4. Chassis ground refers to the metal structure used to support electrical or electronic components. Chassis ground requirements are an extension of the aircraft structure ground in that the bonding resistance shall not exceed .0025 ohms at DC.

5. Schematic coding on each interconnect drawing was devised to explicitly show the method of shield termination, ground at one end only and ground at both ends, for example.

The foregoing design techniques have resulted in an installation that satisfies the system requirements and gives an essentially electromagnetically compatible system.

Airborne Warning and Command Aircraft

Various airborne warning and command programs have been under development to provide a new approach to the command and control function. It is essentially a study program to determine feasibility and cost effectiveness of an airborne warning and command vehicle. Because of its sophisticated mission and its intended use, it may indeed present a bristling array of difficult EMI problems. However, the work that has been performed provides considerable insight into how a wide variety of such problems are handled and is worthy of careful consideration. This type of aircraft with its equipment complement, represents a worst-case situation for current state-of-the-art military aircraft.

EMI Considerations

The airborne RF subsystem consists of multiple receivers and transmitters that provide communication for weapon command and control functions. The subsystem is separately modeled for each purpose, as shown in Figures 16-9 and 16-10.

The RF subsystem uses a large part of the available communications spectrum extending from the HF range of 3 MHz to 30 MHz, up to the UHF range of 225 to 400 MHz. Within that spectrum, as many as 13 receivers and 13 transmitters must operate simultaneously and without mutual interference. Not only must they operate without degradation, they must be compatible with the interfacing equipment and with the aircraft housekeeping electronics. This is a complex task but available EMC techniques can resolve the compatibility problems. These techniques will be used in:

1. Allocation of frequencies on a noninterfering basis
2. Design and test of the subsystem for compatibility
3. Design and test of the units for compliance with the specifications

Frequency Allocation

For an electronics system to be compatible with its operational

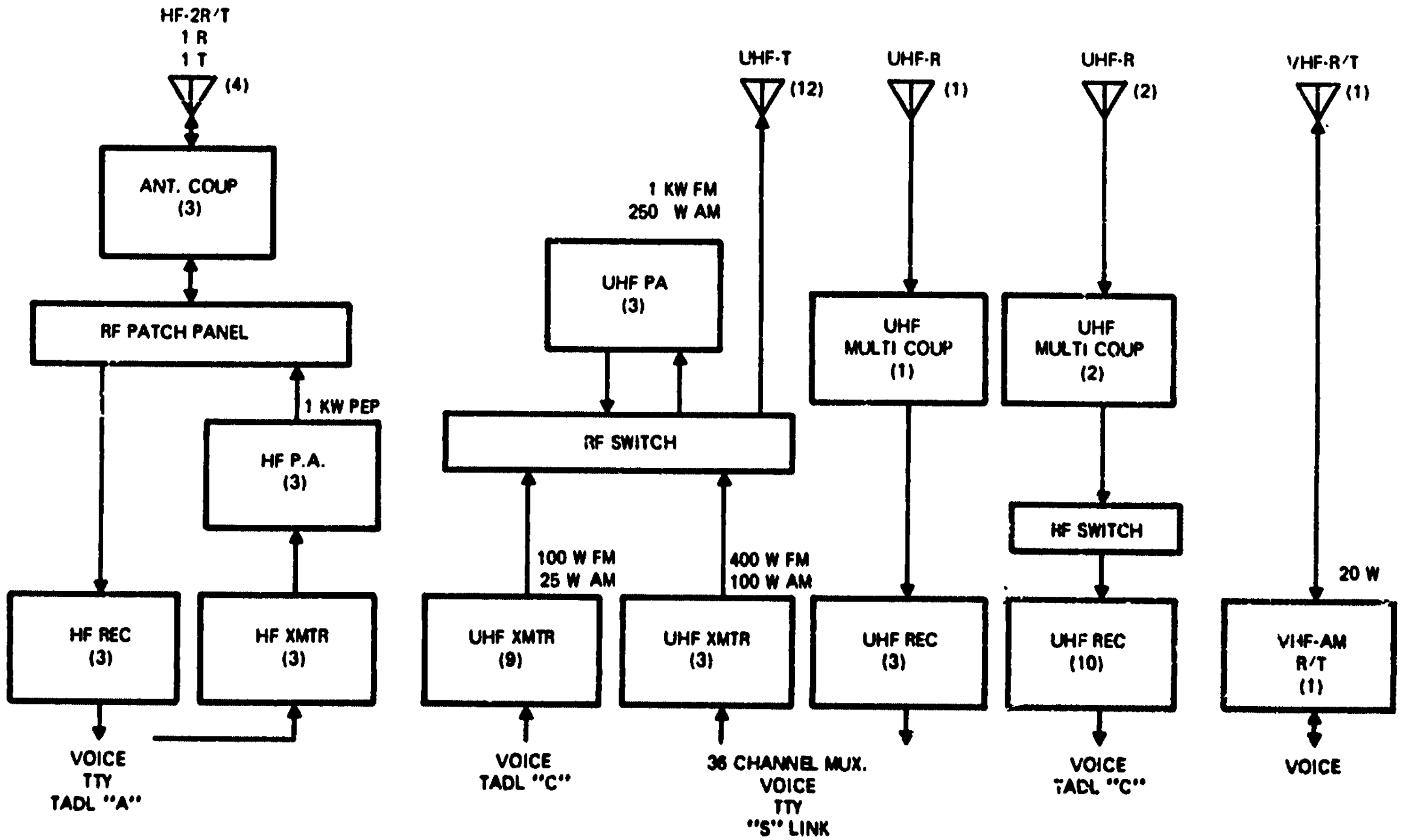


FIGURE 16-9 AIR DEFENSE RF SUBSYSTEM

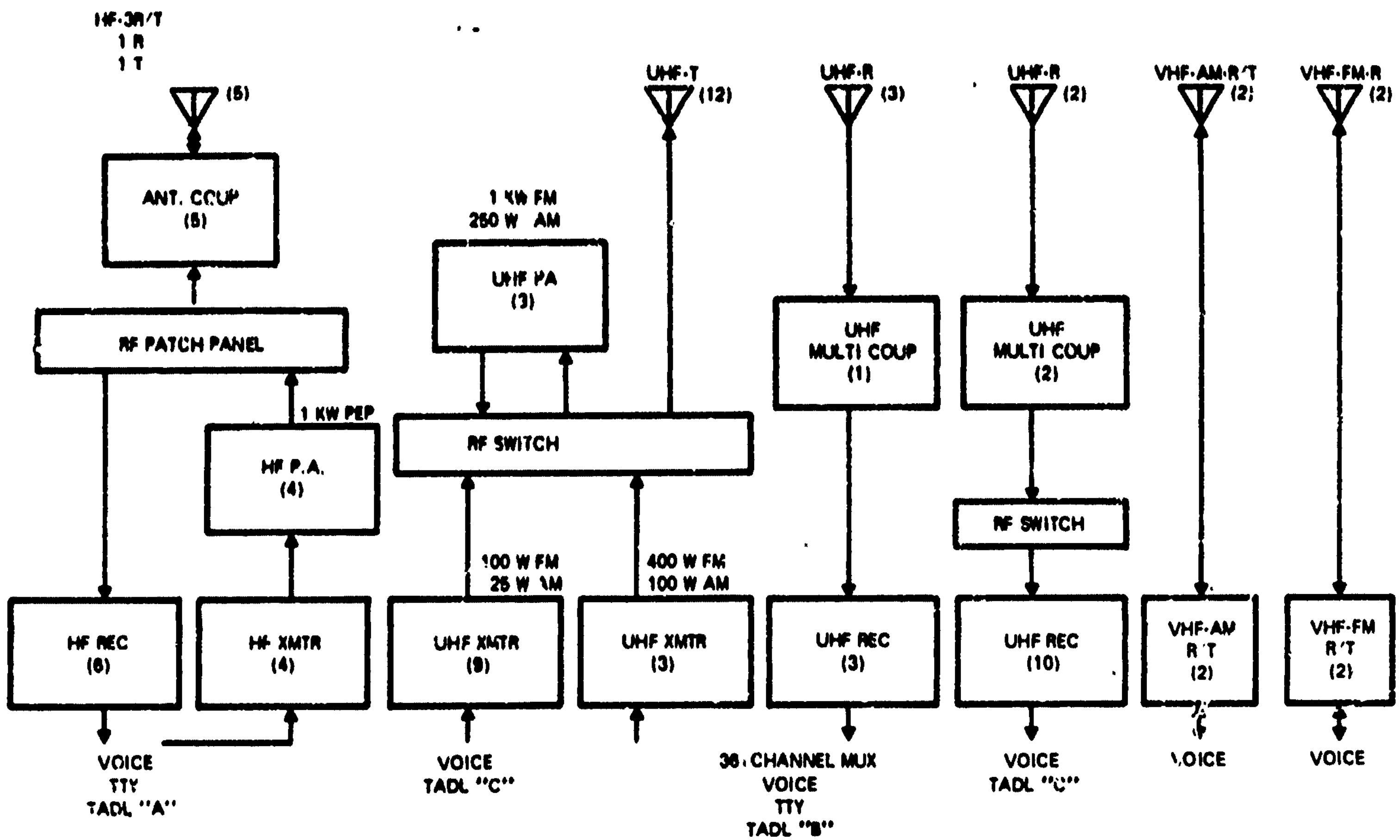


FIGURE 16-10 TACTICAL RF SUBSYSTEM

environment, frequency management restraints must be observed. The RF subsystem must interface with both aircraft and ground weapons and with control systems. These systems are constrained by their environments and consequently cannot arbitrarily operate at any frequency selected by an interfacing source. The interfacing environment will, to a great extent, dictate the frequency assignment. There will be some area of selection left to the subsystem designer, and it is here that the effort must be applied. In the early stages of planning and design, the frequency assignments for each specific subsystem may not be available, and one can only assume a frequency in the assigned bands. To synthesize a system using specific assumed frequencies at this stage would not be sufficiently useful. However, the system can be evaluated in terms of frequency band use based on both experimental data and calculations. Inband analysis resulting in channel separation, front-end bandwidth, preselector requirements, power output, antenna isolation, and signal-to-noise ratio are fairly straightforward. Intra-band effects are not readily analyzed but empirical data are available from past programs such as LEM and Dyna Soar.

Many tools are available for analysis of a receiver/transmitter matrix, which will yield frequency power conflicts as a function of location, power output, and receiver front-end characteristics. Most interference prediction models are complicated and long, and require a computer for a quick solution. Interference prediction models require characteristic data such as spectrum signatures of transmitters and susceptibility or malfunction levels of receivers, as well as the location of the receivers and transmitters. This type of information is not complete in the initial phase of a program, so assumptions must be made. Previous programs provide data for insertion into the subroutines, and results are updated as refined data becomes available. Because of its size and complexity, the airborne warning and command system warrants the use of a prediction model.

Another approach to the selection and analysis of frequencies is by use of mutual interference charts, which plot an array of elements that allows the frequency coordinates of each element to correspond to one receiver channel and one transmitter channel. The interferences are plotted as a function of tuning frequency so that the safe bands are easily identified. This too has been computerized to reduce the time required for a solution. These methods of prediction and analysis should be applied to the subsystem to avoid frequency conflict.

In-Band Considerations

Channel spacing, for the most part, is determined by the type of equipment selected. The HF receiver under consideration has channel capacity of 280,000 channels spaced at 0.1 kHz intervals. The VHF sets under consideration have a capacity of 2500 channels at 50 kHz intervals. UHF sets considered have a channel capacity of 920 channels at 50 kHz intervals. The type of data and modulation (voice and low bid data) in each band appears to be consistent with the available bandwidth and no adjacent channel interference is expected.

However, with the large number of channels available it is wise to provide guard channels between active channels if possible. Simplex operation does not ordinarily offer much of a problem. Duplex operation in which the receiver and transmitter must share a common antenna can be difficult. RF subsystem configuration indicates that for the air defence version, each UHF transmitter has its own antenna, while 3 receivers are coupled to one antenna and 5 each to 2 others.

Maximum advantage should be taken of the isolation offered by judicious antenna placement on the aircraft. The greater the displacement between antennas the more isolation will be afforded. If possible, receiver and transmitter antennas should be on opposite sides of the fuselage to take advantage of the shadow effort.

Figure 16-11 indicates the isolation that might be expected from typical UHF antenna locations.

The measured coupling on a flat ground plane is shown in Figure 16-12 for the UHF band. Tables 16-2 and 16-3 show the coupling between HF probe antennas and between VHF antennas.

Multicouplers considered for this installation are also bandpass filters to aid rejection of spurious signals. For reception, these are required because of the relatively wideband front-end of the receivers. The transmitter output should meet the requirements of MIL-I-26600 or 6181. This may require a filter on the RF output in addition to that of the multicoupler, to suppress spurious synthesizer products and harmonics. Minimum spacing between UHF R/T channels should be at least 5 MHz to assure minimum spillover.

Out-of-Band Considerations

The ability of receiver/transmitter groups at VHF and SHF to operate in the same location can be attested to by experience with the LEM program. Recent EMI tests revealed no mutual interferences between VHF and SHF equipment. Further verification of out-of-band operation is included in the final report of P-band radar, Sage, tactical data system, and UHF Communications EMC report for the Naval Air Test Center.

EMI Black Box Control

Along with frequency management is the practical problem of assuring black box EMI performance. The initial step in the process of EMI control is the generation of an EMC control plan. This plan, a sample of which appears in Appendix B, details the methods of control, the techniques to be used, and the EMC management organization. An EMC specification, if not provided by the contractor, will be written and submitted for approval. The specification will be modeled after MIL-STD-461A and MIL-STD-462 with additions and modifications as required.

After the specification has been approved, the next step is to review the design of all units in or associated with the subsystem. From the basic

	UHF AM-FM (T) STA 410 TOP	UHF AM-FM (T) STA 530 TOP	UHF AM-FM (R) STA 760 TOP	UHF AM-FM (T) STA 370 BOT	UHF/ADF (R) STA 600 K 10 BOT	UHF AM-FM (R) STA 830 BOT	UHF AM-FM (R) STA 880 BOT	UHF ARC 34 (TR) STA 1210 BOT
UHF AM-FM (T) STA 410 TOP	X	27	38	66	66	66	66	66
UHF AM-FM (T) STA 530 TOP	27	X	36	66	66	66	66	66
UHF AM-FM (R) STA 760 TOP	38	36	X	66	66	66	66	66
UHF AM-FM (T) STA 370 BOT	66	66	66	X	36	40	40	43
UHF/ADF (R) STA 600 K-10 BOT	66	66	66	36	X	33	34	40
UHF AM-FM (R) STA 830 BOT	66	66	66	40	33	X	21	37
UHF AM-FM (R) STA 830 BOT	66	66	66	40	34	21	X	36
UHF ARC 34 (TR) STA 1210 BOT	65	66	66	43	40	37	36	X

FIGURE 16-11 ANTENNA-TERMINAL TO TERMINAL ISOLATION IN dB FOR UHF SYSTEMS (ALL VALUES ARE CALCULATED FOR 300 MHz

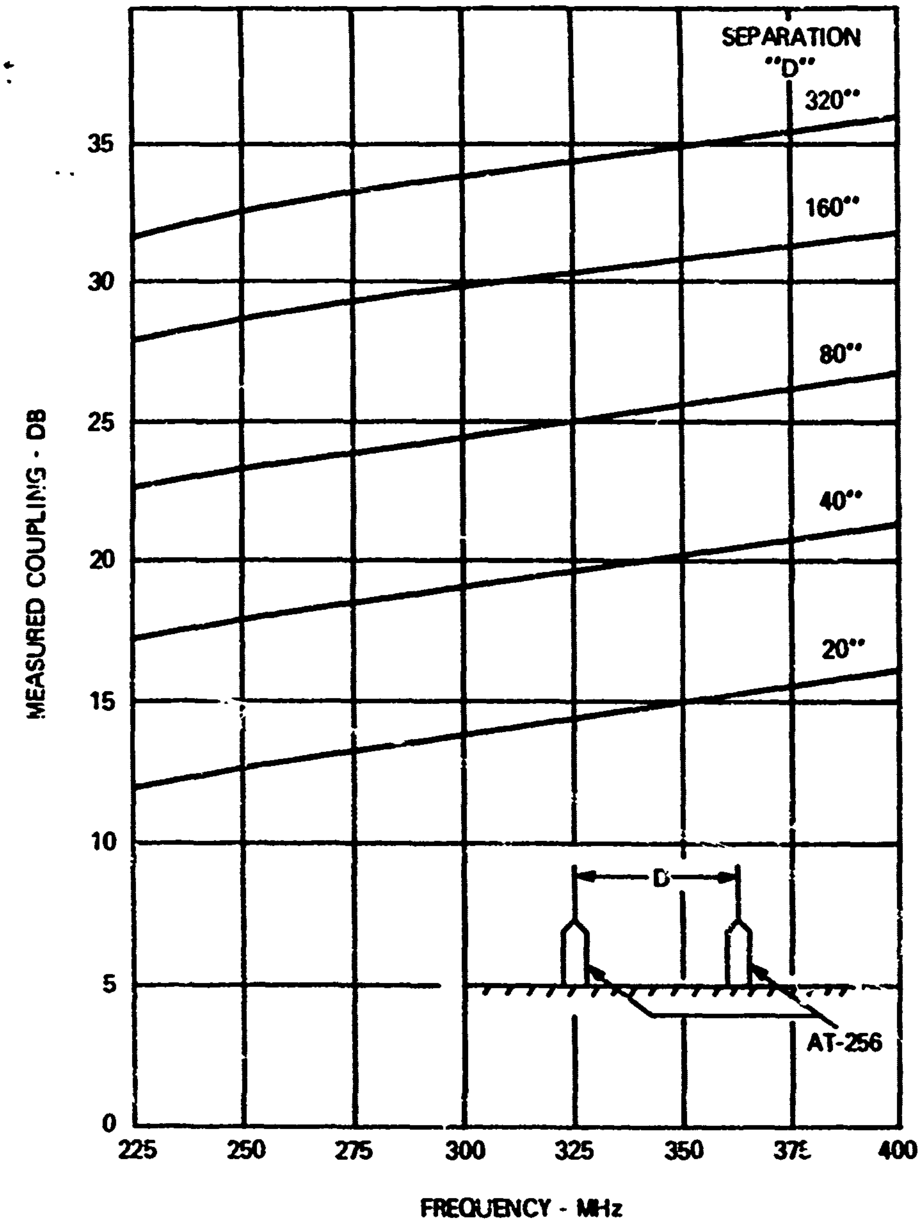


FIGURE 16-12 UHF ANTENNA COUPLING ON FLAT GROUND PLANE

Antenna No. 1 Fin Tip Probe Frequency (kHz)	Antenna No. 2 Wing Tip Probe Frequency (kHz)	RF COUPLING IN DB Antenna No. 1 to Antenna No. 2	Antenna No. 2 to Antenna No. 1
2938.0	2931.0	15.8	15.8
2945.0		16.2	16.2
2966.0		14.7	17.9
2987.0		17.0	19.0
3008.0		17.9	23.0
3023.5		19.5	23.6
4682.5		50.4	40.1
3481.5		29.4	35.4
5604.0		69.0	54.1
4037.0		57.0	59.6
13274.0		46.6	70.6
17926.5		63.0	54.7
13304.5		46.4	70.6
2931.0	13304.5	70.2	48.4
2931.0	17926.5	72.4	36.2
8837.0	17926.5	61.5	44.5
2931.0	8837.0	60.1	50.4
5611.5	5604.0	37.0	37.0
5626.0	5604.0	43.0	46.1
5671.5	5604.0	44.5	47.3
5551.5	5604.0	37.9	39.0
5506.0	5604.0	38.3	46.1
4682.5	5604.0	46.1	38.1
3481.5	5604.0	55.4	62.4
2876.0	2182.0	32.4	37.0
8837.0	8854.0	31.0	32.4
8913.5	8854.0	30.6	32.4
8947.5	8854.0	30.6	33.0

TABLE 16-2 COUPLING BETWEEN HF PROBE ANTENNAS

Frequency	RF COUPLING IN DB	
MHz	Antenna No. 1 to Antenna No. 2	Antenna No. 2 to Antenna No. 1
118	43.6	44.1
123	41.9	42.4
128	42.7	42.2
133	45.1	46.1
136	49.1	50.1

ANTENNA TERMINAL TO TERMINAL ISOLATION - VHF ANTENNAS

	ANTENNA	LOCATION	FREQ. MHz	ISOLATION DB
From	VHF FM 1	STA 470 Top	30	48.0
			50	49.5
To	VHF FM 2	STA 1150 Bot	70	51.0

TABLE 16-3 MEASURED COUPLING BETWEEN VHF ANTENNAS

information obtained, a predictive analysis for each box is performed to indicate the probable levels of conducted and radiated interference, the required levels of suppression, and suppression methods. Predictive data are submitted to the designers for implementation in the design. After design, follow-up test plans and procedures are written by the design groups and submitted for approval to the EMC control group, after which the EMC tests are performed. The reports are then revised and marginal or out-of-spec conditions rectified. Deviations or waivers will be issued only where the change will not affect subsystem performance.

Subsystem Verification

The final step in the EMC process is to integrate the units into an operating subsystem and to test it in accordance with the applicable MIL-STD as tailored by the EMC Control Plan. In this type of test, each unit is played against every other unit in all practical combinations while monitoring the critical signals for malfunction or degradation. A 6 dB margin and worst-case conditions are imposed on the subsystem tests, thereby accounting for measurement errors or unknown performance degradations to assure EMI-free operation.

Effects of Radar

One of the major compatibility problems in the system will be the operation of radar simultaneously with communication subsystems. Radar parameters are not fixed at the present time but some typical values of those considered are shown in Table 16-4. It is not likely that UHF radar will be selected because of component sizes at this frequency; therefore, the S-band appears to be a likely choice. The Raytheon radar may be selected, for example. Its peak transmitted power is one megawatt, and for a pulse compression ratio of 900:1, the average power is 25 kW. The pulse train is 14 msec long and pulse duration 5 µsec. The antenna is a phased array with a scan rate of 6 rpm.

In the pulse compression radar, the transmitter modulating pulse is processed to produce a swept-frequency signal in which the spectral components of a triggering spike are stretched from 3 to 900 times depending upon the type of radar and range resolution requirements. This is achieved by use of an expansion filter that yields the frequency modulated pulse either as a continuous function or in steps. The inverse function is performed in the receiver processor to compress an echo signal back into the original pulse duration. This technique permits high average power for a given peak power while retaining range resolution.

The pulse transmitted by a pulse expansion/compression radar is frequency modulated as well as amplitude modulated and therefore requires much more RF bandwidth than a conventional pulse. The bandwidth depends on amplitude rise time and frequency sweep rate. In the UHF radar, the frequency deviations are in the order of ±150 kHz to ±750 kHz and at S-band may be 10 to 20 MHz. The actual spectrum and sideband energy will be unique for each type of radar.

Table 16-4 Proposed Airborne Warning Radar Characteristics

Radar Characteristics	Raytheon	General Electric	Hughes	Westinghouse	Hazeltine
Frequency Band	S	UHF	S	S	
Radar Type (PRF)	Transmits pulse train 14 ms. long	Low PRF 300	Intermediate PRF (2000) (3 PRF's)	High PRF 50 kHz (3 PRF's)	Search radar (low PRF) & track radar (high PRF)
Peak Transmit Power	1 MW	1 MW	1.2 MW	840 KW	1.2 MW
Average Transmit Power	25 kW	8 kW	8.2 kW	24 kW	20 kW
Antenna Type	Phased Array	Phased Array			Two back-to-back phased arrays
Azimuth Beamwidth	0.78°	6.6°	1.1°	1.3°	4°
Elevation Beamwidth	3.9°	21°	5.4°	4.7°	12°
Scan Rate	6 rpm	6 rpm	6 rpm	6 rpm	15 rpm
Pulse Width	5 usec	27 usec	95 usec	.35 usec	50 usec
Pulse Compression Ratio	900:1	64:1			
Clutter Suppression	double delay-line canceller	double delay-line canceller	range gating and doppler filtering	range gating and doppler filtering	
Ant. Pattern Correction	step-scan	step-scan			step-scan
Motion Compensation	DPCA	DPCA			
Height Measurement	Elevation angle by elevation monopulse	Interpulse Measurement		Elevation angle by sequential lobing	Elevation angle by elevation monopulse
Range Ambiguity Resolution	Pulse-by pulse comparison	Not applicable	Multiple (3) PRF	Multiple (3) PRF	Multiple (3) PRF for track radar

Harmonic energy in pulse radar has been experienced in the kW range for some radars at the fifth harmonic and sub-harmonics. This level is significant at the UHF frequencies and if not suppressed, may saturate the UHF receivers. The source radar must control these emanations by adequate RF filtering and by shielding or pulse shaping.

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NAVAIR 5335

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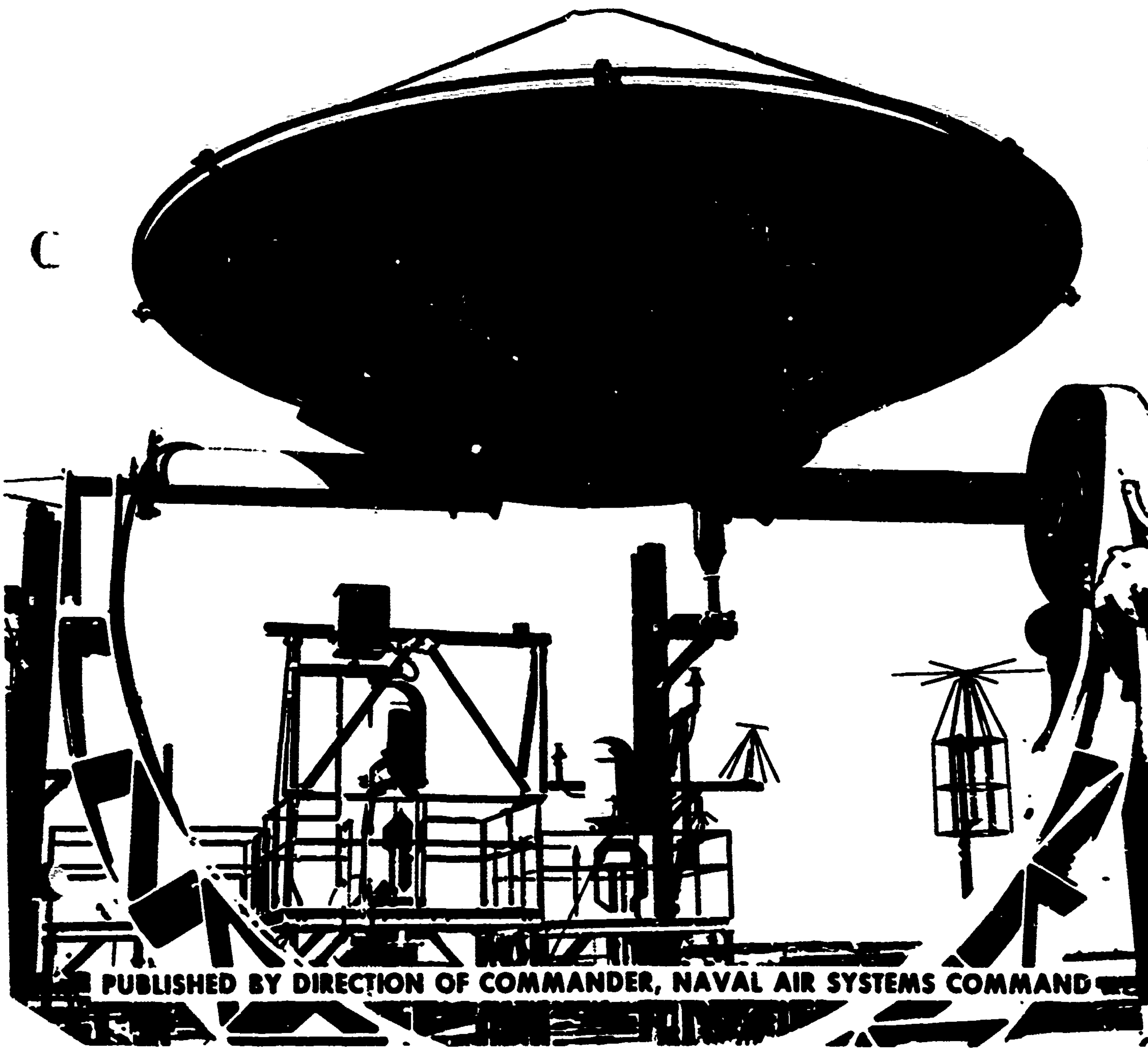
ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 17



PUBLISHED BY DIRECTION OF COMMANDER, NAVAL AIR SYSTEMS COMMAND

CHAPTER 17
INTERFERENCE MEASUREMENTS, TEST EQUIPMENT, AND TECHNIQUES

CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

Interference measurements, including both susceptibility and emanation, use the same methods and equipments used in other areas of radio frequency measurement. With the possible exception of ECM, there is no other area that covers such a wide range of frequencies and signal levels as interference measurements. Consequently, some of the equipments and techniques are specialized and seldom used for any other purpose. This chapter discusses the methods, equipment, and sites used for interference measurements.

Interference measurements, to be useful, must establish definitive limits of EMI emission and susceptibility. To this extent, the field of interference measurements is an eminently practical one. On the other hand, there are many complex areas in interference measurements that require an understanding and an appreciation of fundamentals such as a knowledge of conducted and radiated signal measurements in terms of both signal level and frequency, a knowledge of many diverse test equipments and devices, and a knowledge of the equipment under test.

From these requirements has evolved the recognition that interference measurements are definitely engineering measurements. The problems encountered, the range of frequencies and levels used, the equipment used, and the equipment under examination are factors that keep interference measurements from being considered routine tests. There are situations, however, in which a certain measurement must be performed repeatedly on successive units of the same type, such as in production-line checking, where the measurement can be made routine. The conclusion to be drawn from these arguments is that a useful interference measurement program must be planned and implemented by experienced engineering personnel.

Questions have been often raised as to the accuracy required of interference measurements. In some instances, much time and effort has been expended to resolve the last one or two dB of doubt about the level of a signal. In most cases, this high degree of accuracy is not warranted even if attainable, because many interference signal levels and frequencies vary with time and circumstances. For example, the third or fourth harmonic from a transmitter may vary over as much as ±10 dB, for example as the transmitter is successively retuned to a particular frequency. Similarly, a receiver spurious response somewhat removed from the receiver tuned frequency will not repeat in level as the receiver is successively retuned.

This natural uncertainty in the quantities to be measured leads to the necessity of measuring more than one sample. That is, spurious output levels and spurious response levels must be measured at more than one tuned frequency and for more than one equipment of the same nomenclature. In cases of this type, there is a very real trade-off between the accuracy of an individual measurement and the number of measurements made.

In another related area, that of electromagnetic field measurements, highly accurate measurements are impractical for different but no less compelling rea-

sons. As will be discussed later in more detail, many electromagnetic field measurements performed are of necessity near-field measurements, which constitute an extremely difficult problem under the best of circumstances. In addition, the measurement site is often inside a shielded enclosure such as a screen room, which distorts considerably all components of the field. Therefore, the fields measured can be considered a function of the measurement equipment, test set-up, and test site, as well as the source itself.

These various conditions indicate that extreme accuracy is not often attainable nor is it usually necessary in making interference measurements. This does not make the results any less useful, since the vagaries and variations of emanated signals and susceptibilities must be recognized and allowed for in any realistic compatibility effort. The goal, then, is to measure and record sufficient data under test conditions to be able to predict satisfactory performance under the worst operational conditions.

If an equipment were tested in a signal-free environment, then the measurements would be due to the equipment and the test equipment alone, resulting in easily definable characteristics. An approach to this is the "screen room" or shielded enclosure, which attenuates outside signals and which can keep the internal environment relatively constant. A shielded room can increase the accuracy and the repeatability of measurements, and can reduce or control reflections, if it is designed as an anechoic chamber as well as a shielded room.

For small systems, the shielded room test site is usually satisfactory, but as systems become larger and include ground equipment, vehicle equipment, and perhaps even range control equipment, the shielded room approach becomes out of the question.

TEST ENVIRONMENTS AND CONDITIONS

On-Site Measurements

On-site measurements are defined for this discussion as those made outside a controlled environment or, more specifically, outside a shielded room. The actual locations will vary from a remote communications or radar site, like the DEW line installations, to a factory located in an industrial complex in a metropolitan city where tests on a complex aircraft system may be performed. With respect to on-site EMC tests, the interference test planner rarely chooses the location for tests and as far as possible, must design his program to fit a given environment.

A major problem encountered in on-site testing is that of interference from other sources, primarily man-made. This interference is usually described as the ambient or background level. Most interference specifications indicate that this ambient level should be below the limits given for each of the various tests. From a practical standpoint, while this criterion is desirable, there are very few on-site locations where the requirement can be met at every frequency in the 15 kHz to 10 GHz spectrum. Unless there is a strong cochannel occurrence of ambient signals and signals emanating from the sample, it is probable that the desired tests can be performed.

For the interference test planner faced with on-site measurements, the first step is to evaluate the ambient level at the site. This may be done either directly, by tests, or analytically, by examining the various sources in the area. Each method has advantages and drawbacks. Tests answer some questions that could never be satisfactorily answered analytically in terms of field strengths from particular sources. Also, if just one site is involved and a rather coarse evaluation is satisfactory, only a small amount of time is required for testing. A major drawback of testing, however, is the possibility of missing signals that are not present at the moment the frequency selective voltmeter (FSVM) is tuned to the appropriate frequency. It would take quite a few measurements to obtain an ambient survey that warranted a 95-percent or higher confidence level unless a scanning type FSVM or a spectrum analyzer is used. The analytic approach has the advantage that certain radiators can be assumed to be operating at a particular time and their effect can be judged accordingly. However, the existence of all significant radiators must be known. One major drawback of the analytic method of determining the ambient level is that it is not a simple matter to locate and catalog all sources that might contribute to the ambient level at the test site.

The amount of effort warranted in the predetermination of the ambient electromagnetic background depends, to some extent, on the size of the test program under consideration. For a small job, such as checking an engine-generator set at a manufacturing plant, such an analysis is not feasible. For a job of this sort, the ambient level may be checked at the test location to see if tests are possible. In some cases it will be possible to control the environment for a long enough period of time, perhaps by having machinery shut down temporarily, to perform the required tests. If tests are possible in the presence of high-level interference, these ambient signals should be recorded at several frequencies in each octave, along with the other test data.

During the measurement program, several steps can be taken to improve the possibility of obtaining valid data when ambient signals are a problem. Usually, the ambient or outside signal can be identified to some degree. It may be a signal that is present only randomly, such as the signal from a commercial mobile communications station. It might be practical, in this case, to make measurements while the signal was not being transmitted.

The signal may be arriving at the test site by ionospheric propagation. Such a signal will usually be below 30 MHz and the band will have many such signals, not just one. These signals will not be present for 24 hours continually, however, due to the daily changes in ionospheric propagation, so tests in this frequency range may be postponed until such time as the band is "dead" or relatively quiet.

Certain frequencies in the broadcast FM and TV bands may cause problems. The usual approach in this case is to postpone measurements in these frequency ranges until the offending stations sign off. This approach is also used if certain ambient signal sources are on only during the normal work day. For example, to return to the checkout of the engine-generator set, tests were arranged outside normal working hours so that all the welders, milling machines, lathes, office copying machines, and other equipment could be turned off without disturbing the plant routine.

The characteristics of certain ambient signals allow the human ear to discriminate between them and the signal from the test sample. If this is the case, the aural slide-back method of measurement may result in usable data. This method allows the operator to set a DC bias to the point where an audio signal disappears or, in other words, the operator aurally determines the threshold level of the signal. This approach might be used where the ambient signals are clicks caused by some switching device and the signal of interest is a pulse with a steady repetition rate. The level of the ambient signals should not be too far above the signal of interest, lest the signal of interest be inaudible.

Often interference measurements must be made in areas where other electronic measurements and checkouts are being performed. The managers of these areas can do much toward ensuring that their own ambient level is kept within reason. Certain offending items should be kept out of electronic test facilities or provided with appropriate means of suppression. Several examples are:

1. Vehicles with ignition systems–These may be replaced with diesel units or their interference may be suppressed.
2. Motor-generator sets–These units may be of brushless design or may be located in shielded enclosures with filtered input and output lines.
3. Facility appliances–Certain switching units, such as heater or elevator switches, and many motor units such as refrigeration units and fans, may be selected for installation or replacement under a no-interference criterion.
4. Fluorescent lights–Incandescent lights should be used.

Checkout equipment can produce signals that prevent valid measurements from being performed on the test sample in a shielded enclosure. To correct this, the checkout equipment can sometimes be removed from the enclosure. In some instances, where the test sample may be a large system, the inverse approach may be practical, that is, the checkout equipment may be installed in a shielded room or van to keep the test equipment spurious signal from reaching the test sample. Special attention must be given to all leads that pass through the shield. A more satisfactory solution may be to require the test equipment to meet the same or a similar interference specification as the test sample.

One aspect of on-site tests that should not be overlooked is conducted ambient interference. Ambient signals will couple to power lines and other lines near the test site and be conducted to the test sample unless precautions are taken.

There are some instances in which testing outside of a screen room has advantages. In certain areas, so-called open-site testing may be possible. This requires a location several miles from any concentration of machinery or electronics and also some distance from power lines. Such a site assures a reasonable ambient level, usually limited only by atmospheric noise and signals in known crowded bands such as the TV and HF bands. The advantage of such a site is its freedom from the effects of an enclosure, namely reflections of signals and effects on impedances of sources.

LABORATORY MEASUREMENTS

Laboratory measurements are those measurements performed in a shielded enclosure. The enclosure may be either of two different types: a standard shielded enclosure, the successor to the older screen room; or an RF anechoic chamber.

The standard shielded enclosure offers many advantages and some drawbacks for interference measurements. It has been in use for a number of years for many types of electronic measurements where a low RF ambient level is required, or where signals must be contained. Its use has spread to nonmeasurement applications, such as the protection of personnel near high-power radars and containment of certain industrial RF sources.

The main advantage of the shielded enclosure for interference measurements is the RF isolation it provides from the outside world. Its use allows meaningful emission and susceptibility measurements to be made, both conducted and radiated, in locations where such testing would not ordinarily be possible. Much has been said about the effect of the shielded enclosure on the measurements without carefully pointing out that the principal tests that may be adversely affected are the radiation tests. The main difficulty in making these measurements is that, inside the metal shielded enclosure, there can be multiple reflections of emitted signals that result in standing waves in the room and potential measurement errors. There is no way to avoid this problem, but it may be alleviated to an extent in some measurements by moving the test antenna over a small volume to determine the worst-case susceptibility or inference radiation.

Actual tests in a shielded enclosure will proceed very much like any electronic test. There are several steps that may be taken to expedite and improve measurements. One is to keep the number of people in the enclosure during radiation measurements to a minimum to reduce the variation in the standing-wave pattern. At some frequencies, the movement of personnel can cause significant variation in this pattern, and consequently, variations in the indicated signals. The amount of equipment in the enclosure must be limited to the minimum for operation of the test sample and performance of the test. This will avoid any unnecessary effects on antenna impedances from nearby metal objects.

There is an ambient interference level inside a shielded enclosure because the enclosure only attenuates rather than eliminates outside signals. In a conventional situation where the outside environment is relatively quiet, a modern shielded enclosure will provide sufficient attenuation to reduce all environmental signals to levels below the sensitivity of standard FSVM's. Accoustical type signals (below RF frequencies) would not necessarily be reduced so much. For example, 60-hertz fields can exist both inside and outside the room to the same extent. The walls offer little or no attenuation at these frequencies and power lines can allow easy entry. Additional considerations of shielded enclosures and their features are discussed in another chapter.

The well-designed RF anechoic chamber must first be a good shielded enclosure, and then be further modified or finished into an anechoic enclosure. The concept of an anechoic chamber has been borrowed from the field of acoustics, where it is used for a variety of tests and experiments requiring low ambient audio noise. The two basic requirements of either type of anechoic chamber (RF or acoustic) are high attenuation through the walls and high absorption on the inside walls.

Microwave-absorbent materials such as polyurethane foam, vinyl, and epoxies are used in anechoic chambers. These materials, usually pyramidal in shape, are placed on the surfaces of the chamber to absorb microwave energy. Signals from the test equipment or equipment being tested that are not absorbed by the equipment can be absorbed by the walls so that reflections are prevented or minimized. Cone-shaped sections of the absorbent materials are also available for incorporation in standard shielded enclosures.

In the RF anechoic chamber, exterior noise is attenuated because the chamber is basically a shielded enclosure, while the anechoic properties are achieved by providing an RF-absorbing material on the inside walls. The surface material is usually fastened to all six walls in the form of cones or wedges. Over 95 percent of the incident energy may be absorbed using this technique. The size of the wedge determines, to a great extent, the lowest frequency at which the absorbent material is effective. The lowest practical limit at the present time is about 200 MHz. This rather high frequency, from an interference test standpoint, reduces the usefulness of the RF anechoic chamber for general-purpose radiated energy measurements. However, the room is well suited for use as a "free space" antenna test site for certain types of microwave antennas, particularly those associated with airframes and, more recently, with satellites.

There is, of course, no reason why tests cannot be performed at any frequency in the RF anechoic chamber, but little or no benefit in terms of reduced reflections will be obtained at frequencies below the absorbing material's "cut-off" frequency.

Shielded Enclosure/Anechoic Chamber Construction and Features

Shielding theory and materials are discussed extensively in another chapter, so they will be discussed here only as they relate to certain aspects of screen room construction.

Earlier in this chapter, it was indicated that electronic systems may eventually become too large to be tested in a shielded enclosure. While this is certainly true, the size of the enclosure has no theoretical limit, and enclosures have been built to sizes that the user of an 8-foot by 10-foot by 10-foot enclosure would consider quite large. For example, the Titan ICBM is checked out in a five-story shielded enclosure, which also has a five-story door. The Navy Air Test Center at Patuxent River has a large aircraft hangar designed as a shielded enclosure, and others are being planned.

Shielded enclosures also exist in mobile configurations. Several government agencies and industrial firms have mobile electronic laboratories, which are

shielded enclosures constructed in a trailer or van. They may be simply mobile or portable screen rooms for general-purpose use, or they may be used to perform measurements in high-field areas where protection is necessary for personnel and equipment.

All metals, and even a few non-metals, have shielding capability under some circumstances. Either steel or copper is usually used as the basic material in a shielded enclosure. The steel is usually in the form of galvanized sheet, while the copper is either in sheets or fine mesh screening. Which material is used will depend on weight restrictions, cost, shielding desired, and other variables. For equal cost, steel will probably furnish performance equal to copper at frequencies down to 150 kHz, at which point the permeability of steel begins to provide improved magnetic field shielding.

In measuring radiated energy, consideration of the effectiveness of low-frequency shielding should include magnetic field (H) as well as electric field (E) measurements. To determine shielding effectiveness at frequencies below about 500 kHz, only the H field measurement need be performed, since the E field attenuation is invariably superior.

The first of the modern shielded enclosure construction methods was developed, to a great extent, at the Johnsville, Pennsylvania, U. S. Naval Air Development Center. This room was made with two layers of copper screen separated by about an inch. The room was constructed of several panels, called cells, each one 8 feet by 4 feet. The individual panel edges butted together and were bolted through the wood framing that provided the shape and strength for each panel. One of the features of this room was that it could be disassembled, moved, and reassembled at a second location without major modification.

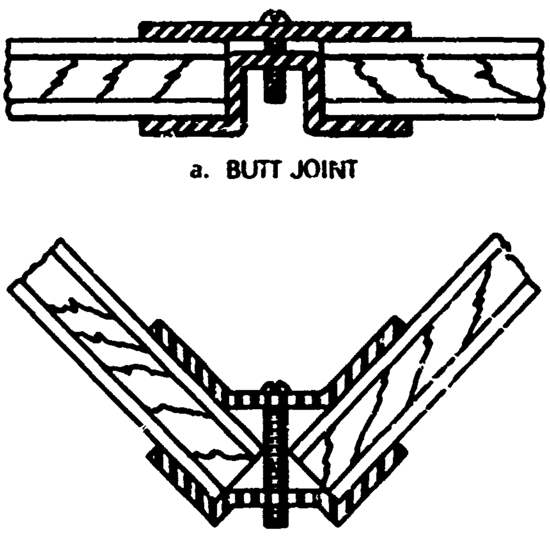
The door for this room was framed with well-braced wood and covered with either sheet copper or copper screen. The periphery of the door was furnished with two sets of spring fingers, one to provide contact with the inner edge of the door-jamb and sill, with the outer set to push against the outside of the door frame. This second set of spring fingers actually overlapped the door frame opening.

A similar enclosure construction is the cell type with only a single layer of screening or sheet. This method is not widely used since it is almost as expensive as the double-layer cell-type and has poorer performance. There has been a long-standing controversy over the supposed advantage of completely separate layers in the double-shielded room as opposed to the cell-type room just described. Theoretically, it would seem that the true room-within-a-room might actually perform better, but by the time theory is reduced to practice, it is not always so clear. This type of construction is presently available.

Another type of construction makes use of a single sheet on a metal framework. The sheet is under some tension from the way it is fastened to the frame, and the frames or panels are bolted together with through bolts.

A fairly simple method has been developed recently for double-layer enclosures, or the so-called double-shielded room. This is the sandwich panel, with two steel sheets bonded to a 3/4-inch plywood core. The panels are not butted together all the way, but are clamped on each edge by special continuous channels

and strapping. The method of joining panels along the sides of a room and at the corners is shown in Figure 17-1. Machine screws pull the channel and strap together every few inches. Doors for the newer shielded enclosures are not much



a. BUTT JOINT

B. CORNER JOINT (VERTICAL OR HORIZONTAL)

FIGURE 17-1. METHODS OF JOINING SANDWICH-TYPE PANELS.

different in concept from the one first described. They are perhaps stronger, with stronger door frames as well, to provide better attenuation around the door. They still use two rows of metallic fingers to make a good seal between the door and door frame. There are some improvements in the latching arrangements, so the door may be opened and closed easier.

These basic construction methods are suitable for rooms of many sizes. For rooms that are larger than approximately 10 feet in both floor dimensions, structural members are added outside the room to provide truss support of the ceiling weight. If unusually large doors are required, they are supplied with a wheel to support the weight of the door directly and relieve the hinges.

Figure 17-2 shows a room-size enclosure of welded seam construction. The two doors are of the pocket-type sliding design. When the doors are closed, a pneumatic system exerts a pressure between the door and the jamb to produce a good bond between the door panels and the walls. Power line filters are mounted on top of the room. The panel on the side of the room has coaxial cable connectors installed on it so that signals can be transmitted through the wall as required by special tests.

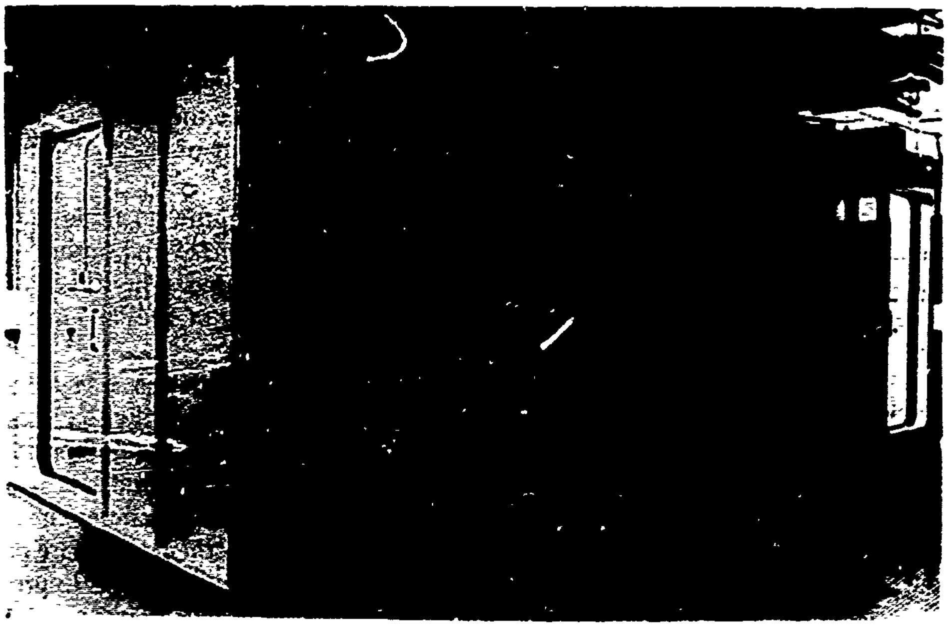


FIGURE 17-2. ROOM SIZE SHIELDED ENCLOSURE

Part of attenuation for a shielded enclosure is provided by the structure itself, the wall sections, seams, and door. But these are of no value, no matter how well designed, if the room is penetrated by any unfiltered lines or wires. For this reason, power-line filters are an integral part of the enclosure.

The basic requirement for the filters is that they provide a certain minimum attenuation over the frequency range of the room, usually from approximately 10 kHz to 10 GHz. The electrical design of such a filter is not especially complex, as can be seen from the material on filter design in another chapter of this manual. It will, however, require several filter sections to provide satisfactory attenuation.

The difficult problem is to determine how much attenuation the filters must offer to complement a particular room design or application. The degree of attenuation that must be furnished by the filters is only roughly related to the attenuation of the room. If strong ambient signals are present, they will appear in both the surrounding fields and on the power lines. It is the relationship between the two levels that is subject to many variables and therefore difficult to judge. It is also possible that the power line will bring into the shielded enclosure area signals that would normally not be a factor of the environment. A filter that resonates at the power line frequency can cause abnormally high AC voltages to appear on the power distribution bus.

The usual solution to the problem is to provide filters with attenuation capability somewhat less than that of the room. For example, if the room offers attenuation of 120 dB over most of the frequency range, filters offering 100 dB should be adequate. If experience with the particular installation shows that the filters, even though properly installed and meeting their specifications, do not

provide the necessary attenuation, additional filters may be placed in series to provide the additional attenuation. Normal installation practice places the filters outside the enclosure, with the line coming through a pipe nipple into the room. If additional filters are required, they should be installed inside the room, so that the enclosure walls provide good isolation between the input of the first filter and the input of the second.

The mechanical design of high-attenuation filters is quite an important factor in their performance. To reduce coupling between the input and output of the separate sections, well-designed compartments are required. The buyer of power-line filters must be cautious in his selection, as a variety of sizes and qualities of shielded enclosure filters is available.

Shielded enclosures of all types require some forced ventilation, especially the solid-wall enclosures. This must be provided without affecting the shielding effectiveness of the walls. The standard method of achieving this requirement is to use the waveguide-beyond-cutoff principle, and there are several satisfactory physical configurations. The concept is to provide many small-diameter tubes whose length is at least three times the diameter, and arrange them in a more or less parallel configuration. Each tube must be well bonded to the others to preclude leakage through cracks and seams. The finished unit, sometimes termed "honeycomb," may look like an automobile radiator. The placement and size of these air vents will depend on the individual room requirements, as will the size and type of blower. If the room is to contain large amounts of equipment or many persons, air conditioning might be furnished.

Additional penetrations of the enclosure walls may be necessary to provide other services; gas, water, and compressed air may be furnished through steel or copper piping. If the pipe is joined to the enclosure wall in a clean, tight connection, the attenuation of the room will not be appreciably affected.

The same method must be used to bring coaxial lines through the wall of the enclosure. In this case, special coaxial fittings are available that are similar to a threaded pipe nipple, except they have the suitable coaxial construction and fittings at each end. The use of coaxial cables can, in some cases, reduce the shielding effectiveness of an enclosure by providing a path of entry for high-level signals. These high-level signals can penetrate the cable shield and be conducted into the enclosure. Therefore, if high ambient signals are known to exist, double-shielded coaxial cables should be used.

There must be lighting in the enclosure. This should in all cases be incandescent, because other types of lighting usually involve ionization processes and subsequently produce RF noise. There are some fluorescent fixtures that have RF suppression built in. This type of lighting may be usable in a laboratory, but it is definitely not suitable for shielded enclosures. Any other services to be provided such as electric heating, should be installed so that it cannot produce any RF signals.

Shielded enclosures require a certain amount of maintenance if they are to retain their designed attenuation. The vulnerable areas of a shielded enclosure are the joints, the seams, and the door. The enclosure manufacturer usually gives a torque rating on the fasteners so that periodic checks of the proper force be-

tween fastenings and panels can be made.

The finger stock along the edge of the door must be kept in good condition. If any fingers are damaged or broken off, a new section of fingers may be soldered on as a replacement. These fingers provide a good connection between the enclosure and the door by sliding, for a short distance, along the door frame. To maintain a good connection, the door frame must be kept smooth and clean.

All the facilities associated with the screen room must also be kept in good condition or they will affect the operation of the enclosure. For example, the incandescent fixtures may eventually develop faults that result in the production of RF noise.

A newly installed shielded enclosure usually receives a thorough check of its attenuation to determine if it performs according to specifications. These tests are performed in accordance with MIL-STD-285, which prescribes test frequencies and equipment, as well as antenna separation distances. The testing of a screen room is basically a near-field measurement, which means that the results may vary widely as a function of distances, antenna types, and frequency. For this reason, it is important that the methods indicated in MIL-STD-285 (if it is the test specification) be followed as closely as possible so that meaningful and repeatable results may be obtained.

An installed, shielded room should be tested periodically to verify that the enclosure attenuation still meets the original specification. In this respect, the enclosure may be considered as an item of equipment in the laboratory inventory and placed on the periodic calibration schedule.

After the initial checkout, the enclosure should be checked at least every other year. Interim spot checks may be desirable in conjunction with special interference tests as a validation move, or if degradation of enclosure attenuation is suspected.

Most shielded enclosures are produced by specialists who have considerable experience in the field. The following list of manufacturers is not all-inclusive and is arranged alphabetically.

Ace Engineering and Machine Co., Inc.
Huntingdon Valley, Pennsylvania

Emerson & Cuming, Inc.
Canton, Massachusetts

Erik A. Lindgren & Associates, Inc.
Chicago, Illinois

Filtron Co., Inc.
Flushing, New York

LectroMagnetics, Inc.
Los Angeles, Calif. 90016

Ray Proof Corp.
Stamford, Connecticut

Topatron, Inc.
Garden Grove, California

INTERFERENCE TEST EQUIPMENT

TYPES AND PURPOSE

Interference test equipment may be divided into two broad categories: general and special. General test equipment includes signal generators and electronic voltmeters, while special test equipment is that developed specifically for interference testing. This latter category is primarily made up of various frequency-selective voltmeters and their accessories, plus a few special-purpose units. Both categories will be discussed in this section.

The keystone of interference measurements is the frequency-selective voltmeter (FSVM) or calibrated receiver. The pickup devices used with these receivers include various types of antennas and probes, some calibrated to provide absolute measurements and some useful only for relative measurements. There has been significant progress in this area in the last fifteen years, but there is enormous room for further advances. A retarding factor, of course, is the relatively narrow market for such equipment and the difficulty of meeting particular specifications of the various users.

Low-power signal generators, on the other hand, are probably the most widely used single category of equipment in the electronic industry. In interference measurements, they provide both desired and undesired signals for the various tests, as well as accurately known levels for substitution measurements. Even in this area, however, the interference test planner finds considerable room for improvement. For example, many generators do not have enough harmonic suppression to permit their use in some tests without external filters.

Various special devices are required for interference tests. These include impulse generators for calibration and signal substitution measurements, transient generators for susceptibility tests, and several audio equipments for audio susceptibility tests. These equipments will also be discussed in some detail.

As electronic systems become more complex, the interference test planner finds himself devising his own instrumentation, due either to a difficult test specification requirement or to a special test requirement not necessarily associated with a specification. This is especially true of avionic systems with their ultrasensitive receivers and high reliability requirements. In instances of this sort, it is generally more convenient and economical to use modified existing equipment and perhaps provide additional auxiliary units than to develop a completely new instrument. For instance, there are several arrangements suitable for increasing receiver sensitivity if that becomes necessary. In some frequency ranges, preamplifiers with low noise figures are available, or preselectors may be used to reduce the bandwidth. In other instances, the bandwidth may be reduced by using a second low-frequency receiver as a tunable IF amplifier.

Various other types of special test equipment such as high-level or high-stability signal sources may have to be devised. Here again, the most suitable approach is to adapt existing instrumentation if at all possible.

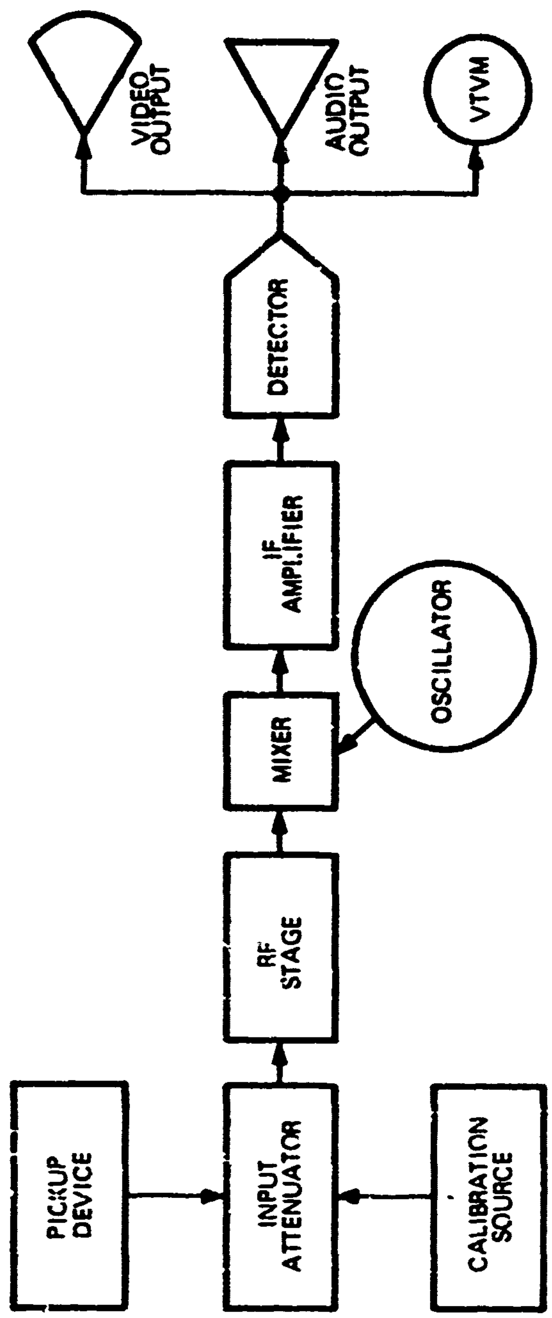


FIGURE 17-3. BLOCK DIAGRAM OF A TYPICAL FREQUENCY-SELECTIVE VOLTMETER.

Equipment Characteristics

As mentioned previously, the frequency-selective voltmeter is the keystone of the interference measurement field. It is basically a well-shielded sensitive

radio receiver with a wide dynamic range and calibration for absolute measurements. These instruments are available to cover a frequency range from 30 hertz to 20 GHz, from subaudio frequencies to a wavelength of 1-1/2 centimeters.

From the block diagram in Figure 17-3 it is evident that the FSVM is a superheterodyne receiver with some added features. The block diagram shows only one possible receiver; there are many other configurations. A recent configuration receiving attention is the zero-IF or direct conversion receiver that eliminates the IF amplifier stages and their bandwidth limitations. Each of the major blocks on the diagram will be discussed briefly in the following paragraphs.

Pickup devices provide coupling from the signal source to the FSVM. Two types of coupling are possible: direct or by means of the electromagnetic field.

Direct coupling may be accomplished readily since all currently used FSVM's have some means of providing 50-ohm inputs. Their inputs may be connected directly to 50-ohm source circuits or through directional couplers, attenuators, or filters where necessary. They are usually coupled to power lines, AC or DC, with a particular network termed a line impedance stabilization network (LISN). This unit will be discussed in detail later, along with a device with a similar purpose, the current probe. These units are generally not considered part of an FSVM.

Type of Measurement	Type of Antenna	Frequency Range
Magnetic field emission	Loop	30 Hz – 30 kHz
Radiated emission	Rod	14 kHz – 25 MHz
Electric hand tool measurements	Rod	14 kHz – 30 MHz
Radiated emission	Biconical	20 MHz – 200 MHz
Susceptibility	Biconical	20 MHz – 200 MHz
Emission and susceptibility*	Conical log spiral	200 MHz – 10 GHz
Harmonic and spurious output	Cavity-backed spiral	200 MHz – 1 GHz
Harmonic and spurious output	Cavity-backed spiral	1 GHz – 12 GHz
Harmonic and spurious output	Horn with 18-inch dish	12 GHz – 18 GHz
Harmonic and spurious output	Horn with 12-inch dish	18 GHz – 40 GHz

*Except for harmonic and spurious outputs in the open field.

Table 17-1. Test Antennas Specified in MIL-STD-461A

Electromagnetic field coupling is provided by an antenna. In some cases, a small uncalibrated probe antenna may be used, as when a leakage source is under investigation, but calibrated antennas must be used to obtain an RF field measurement in absolute units. A wide variety of antennas is in current use to cover the required frequency range, but there has been a recent trend to use antennas that do not require adjustments, such as broadband antennas. Types of antennas currently used according to MIL-STD-461A and the frequency ranges they cover are listed in Table 17-1.

The vertical rod antenna, one of the more fundamental types, is usually a collapsible unit extending to about 41 inches. Other lengths are used, but the 41-inch antenna is specified in MIL-STD-461A and elsewhere The electrical length of this antenna will be about one-half its physical length, making the conversion of voltage measured at its base to field strength units (volts per meter) quite simple. Twice the meter indication will be the field strength. Near-field conditions will normally exist for all interference measurements made below 400 MHz or so, which means that the rod antenna will indicate only the electric field component. This is not necessarily a drawback, if it is recognized by the measurement personnel. It should also be recognized that this antenna, along with all other linear antennas, is polarization-sensitive. Because most interference signals are linearly polarized, the level of the received signal will vary to some extent with antenna orientation. Whether or not measurement procedures require the maximization of a signal by orientation of the antenna depends on the particular specification involved.

To measure the low frequency range from 30 Hz to 30 kHz, a loop antenna must be used as indicated in Table 17-1. MIL-STD-461A specifies one form for magnetic field emission measurements and another form for radiating magnetic fields during susceptibility measurements. The loop antenna is useful for measuring magnetic fields for frequencies up to 30 MHz, but to retain the normal loop pattern, the diameter of the loop should be about one tenth of the shortest wavelength to be measured. To provide attenuation to electric fields, most loops are provided with an electrostatic shield. As with the rod antenna, the loop is also polarization-sensitive.

The rod antenna is an unbalanced device, that is, one terminal is normally grounded. The loop antenna, on the other hand, is balanced; both terminals are ungrounded. To efficiently connect this antenna to the normally-unbalanced FSVM input requires some additional device or circuitry. A balun (balanced-to-unbalanced transformer or network) will do the job and should always be used with balanced antennas. When required, baluns are normally built into the antenna mounting or base.

For the frequency range from 30 MHz to 1 GHz, half-wave dipoles have been traditionally used. These are balanced, linear, and resonant antennas with an impedance of about 72 ohms. While it is true that they are basically an electric field pickup device, this fact does not have the importance it did below 30 MHz. Their major drawback, as far as interference measurements have been concerned, is the necessity for constant readjustment as a frequency range is swept. Normally, adjustments should be made at 10-MHz intervals to 100 MHz,

at 25-MHz intervals to 400 MHz, and at 50-MHz intervals to 1 GHz. Adjustments should also be made at each measurement frequency. To overcome the adjustment requirement, several broadband antennas have been devised. The bowtie, which is similar to a dipole, has been used from 400 MHz to 1 GHz.

The conical-spiral antenna differs from most interference pickup antennas in that it is circularly polarized and thus does not require adjustment for either polarization or tuning.

To provide absolute field strength measurements from the voltage at the antenna terminals, it is satisfactory to use theoretically-calculated antenna factors for the half-wave dipoles. This factor will include the correction for the electrical length of the dipole, π/λ, as well as any correction for the mismatch between the antenna impedance (72 ohms) and the FSVM input impedance (usually 50 ohms). Factors for the other antennas discussed here must be determined experimentally. Usually, this may be done by comparison with a half-wave dipole, both antennas being immersed in the same plane-wave field.

Another type of broadband antenna used to a small extent in interference measurements is the discone antenna. This antenna normally does not require adjustments, although it is sometimes furnished with rod-type extensions to increase its effective electrical size and extend its low frequency range. This antenna must also be calibrated initially against a known antenna. The discone antenna is also suitable for use in the 1- to 10-GHz range, but will reduce the over-all sensitivity of the measurement setup due to its relatively low gain. It may be useful in situations where its more omnidirectional properties are an asset.

More recently, another type of broadband antenna has come into use. This is a reflector-type antenna with a log-periodic feed structure. Its use makes changing antennas to cover the entire frequency range unnecessary. As with other antennas, it must be calibrated against a known antenna.

To provide signal pickup devices in the 1- to 40-GHz range, a set of microwave horns, some with reflectors, has usually been used. These horns are linearly polarized, which indicates a sensitivity to orientation, but they do not require any adjustment. Rather, they are furnished with a calibration curve to convert calibrated meter readings to field strengths, or in this frequency range, sometimes to power densities.

The input attenuator is a device that gives the FSVM its usually large dynamic range. The attenuator used on most FSVM's consists of a set of coaxial barrel attenuators, providing attenuation in steps of 10 or 20 dB from 0 to 80 dB. The attenuators must have good RF properties over the range of the instrument, and have some power dissipation capability. An added benefit of the attenuators is the stabilization of input impedance over the frequency range. If one of the barrel attenuators is in use, a 50-ohm input impedance will be presented. It should be noted, however, that the first step, in some cases, is not at the receiver input. In these cases, the FSVM probably will see a less than ideal input impedance for both the 0 dB and the first attenuation positions of the input step attenuator.

Due to the variation in gain with frequency, the usual FSVM must be cali-

brated at each measurement frequency. This is usually done in one of two ways. Either an internal source is used in conjunction with a gain control to set a reference level (with the input attenuator being depended on for translation to other levels), or the FSVM is used simply as a transfer device with each measured signal being matched exactly by a signal from an external source. The method used will depend upon the specification used, the accuracy required, and other circumstances. The methods are similar in that each one requires a known source. If the reference is set only on one setting of the input attenuator, only a single-level signal is required; in contrast, a wide range of levels, as from a standard signal generator, is required for the substitution method.

Calibration sources include CW, random noise, and impulse noise sources. The CW source is analogous to the standard signal generator. The random noise source provides a wideband repeatable signal that must be initially calibrated against a CW source. The impulse method is also a wideband repeatable source, but has been more highly developed than the random noise source. The impulse generator usually operates by generating an extremely short pulse (5×10^{-10} second, for example), which has a flat frequency spectrum over a wide range of frequencies. This pulse may be generated by alternately charging and discharging a short length of transmission line. The dependability of the spectral output will then be only a function of the charging voltage and of the physical condition of the transmission line and its charge-discharge mechanism.

Many FSVM's have internal impulse generators with widely variable outputs that can be used either for precalibration or for substitution measurements. It should be noted that to use impulse calibration for CW measurements requires either information about the instrument bandwidths or comparison with a CW source at the desired frequency. Normally, enough information is furnished with the FSVM to allow complete calibration with an impulse generator.

The RF stage serves several functions in the FSVM. It provides, of course, some gain to increase the sensitivity of the unit. It also provides isolation between the mixer-oscillator section and the antenna terminal. This is important to prevent the local oscillator signal from appearing at the antenna terminal and, in some instances, confusing the measurement situation.

Probably the most important function of the RF stage is to provide rejection of undesired signals and to prevent, as far as possible, intermodulation. An RF stage fulfills this function in two ways: by providing selectivity with its tuned circuits, and by providing linear amplification over a wide dynamic range. Successful accomplishment of these two objectives allows an FSVM to measure small signals in the presence of large signals. In addition to the normal tuned circuits, low-pass, high-pass, and bandpass filters may be used to increase the rejection of out-of-band signals.

A desirable, though not vital, feature of RF amplifiers is the constancy of gain across the tuning range. If gain could be kept constant through the mixer stage, only one calibration per band would be required. At the present time, this is only practical in VLF equipment where the RF amplifier may be wideband, but future developments may allow the improvement to be added at higher frequencies.

Vacuum-tube RF amplifiers in the conventional sense are not used in the microwave ranges. Here. the first active stage in the receiver will probably be a crystal mixer. However, passive preselectors are used to reject off-tuned signals. These may be in the form of resonant cavities, and up to three may be used in a mutually-coupled configuration.

Microwave FSVM's usually have large noise figures, on the order of 20 dB or higher, due to the crystal mixer configuration. If a better noise figure is required, it may be obtained by the addition of some form of parametric amplifier or low-noise traveling-wave-tube (TWT) amplifier. It should be possible to obtain a noise figure of a least 10 dB or smaller by the addition of such a preamplifier.

The oscillator and mixer stages in an FSVM are relatively conventional. The properties that are sought in these stages for communications receivers are also sought in the FSVM. The oscillator signal must be stable, particularly if the instrument has a narrow bandwidth or is to be used in a narrowband setup. The oscillator stage should, of course, track with the tuned RF stages if any, to retain the smoothest practical gain-frequency characteristic.

Crystal or vacuum-tube mixers may be used, although the poor efficiency of vacuum-tube mixers at UHF and above precludes their use above several hundred megahertz.

A frequency synthesizer may be used in an FSVM to produce local oscillator signals in increments of high frequency accuracy. In this case, the increments must be spaced at intervals less than the overall instrument bandwidth to provide continuous coverage. Frequency synthesizers have an inherent disadvantage in that they produce other frequencies in addition to the desired frequency, which results in more spurious responses than for the same receiver with a conventional oscillator. Spurious responses are particularly undesirable in equipments used in interference measurements.

The IF bandwidth of the IF amplifier should usually be less than the RF bandwidth, so that the over-all bandwidth will be determined by the IF stages. In this way, variations of RF bandwidth with frequency will not affect the instrument bandwidth.

Because of bandwidth limitations and spurious responses in the conventional RF/IF FSVM, the direct-conversion or zero-IF receiver configuration is receiving favorable attention. The direct-conversion receiver uses no RF or IF stages, hence has no tracking problem, and image responses are more easily controlled. RF input signals are applied directly to a balanced mixer for conversion to a frequency range from 0 Hz upward. Mixer output is routed through a filter (which can be of any practical passband) to an operational amplifier. Bandwidth is controlled almost entirely by the filter. In fact, by branching out from the mixer, a number of bandwidths can be observed and tested simultaneously. The gain-bandwidth product is comparable to the more conventional FSVM.

In some instances, it is desirable to use dual conversion in FSVM's. At higher frequencies, this method is necessary to provide sufficient amplification and spurious response rejection. It is also generally better to use this method to arrive at a lower IF frequency than to convert in one step from a high tuned frequency stage.

Conventional receiver practice in the past has been to narrow the bandwidth to improve receiver sensitivity. While this is a proper approach for CW signals and is only limited by the signal bandwidth and the combined stability of the local oscillator and the signal, it is not the correct approach to improve receiver sensitivity to impulsive signals. With all other parameters constant, the receiver's own random noise voltage, produced in the first one or two stages, will increase as the square root of the bandwidth increases. However, impulsive noise voltage increases directly with an increase in bandwidth, which indicates that to produce maximum receiver sensitivity to impulsive signals required the widest bandwidth receiver that is possible. There is, of course, no benefit if the receiver bandwidth is wider than the bandwidth of the signal. This consideration is particularly important in radar work and has been recognized in the FSVM's designed for this range. They are furnished with two bandwidths, one less than 1 MHz, and the other on the order of 3 to 5 MHz. FSVM's for lower frequency ranges may have a variable bandwidth to take advantage of this method of improving sensitivity to impulse signals.

Dynamic range is as important in the IF stage as it is in the RF stage. The IF amplifier must be linear over the range to be read on the output meter, with some additional capability. Signals with high peaks should not be allowed to overload the amplifier even though the detector is being operated in an average mode. Input and IF attenuators are provided to extend the dynamic range, and their settings must be applied to the meter readout. The upper working limit of an FSVM can be further extended by using external attenuators.

In some instances, it is helpful to have an IF output terminal on the FSVM. This will enable the test planner to use special detector techniques or spectrum analyzers instead of the ordinary detecting methods. The IF output may also be fed into a second FSVM to further reduce the FSVM system bandwidth. The output circuit must be so arranged that its use will not affect the other circuits if several detection or analysis methods are to be used simultaneously. Some FSVM's provide a restored frequency (post-IF) output which can be used by other test instruments such as a frequency counter.

The detector stage in an FSVM has the function of separating signals according to modulations, or perhaps more accurately, according to their peak-to-average ratio. This is done by using several different charge and discharge times for the detector. As the charge time is decreased, the detector circuit becomes more responsive to short-duration, fast-rising signals. As the discharge time is lessened, the detector circuit will tend to dump or lose the charge of a signal in a shorter time. Therefore, to provide a detector that responds to CW signals, an average function is provided. With the detector operating in this mode, the charge and discharge times are both 600 milliseconds. This is the mode to be used when measuring CW or simply modulated signals. The output meter will indicate in rms volts.

By appropriately altering the charge and discharge times, a peak detector may be obtained. A peak detector will have a very short charge time, on the order of tens of microseconds, with a long discharge time, on the order of hundreds of

milliseconds. This results in a metering circuit that will respond quickly to the highest signal and "remember" it over a short interval.

There is another widely used means of peak-detecting, commonly referred to as the "slideback" method. The detector constants are about the same as for the average mode, but there is now a DC bias that is adjusted by the operator until the audio just disappears or is at the threshold of audibility. The operator, in effect, matches the peak of the signal level with a DC level that is read on the metering circuit. This aural slideback method offers the possibility of measuring one signal in the presence of another when the desired signal may be somewhat lower in level. Otherwise, the visual peak methods referred to as direct peak reading are preferred. They reduce the time required for measurement and also reduce the subjectivity experienced in the aural method.

In the past, another detector function was widely used. It was the quasi-peak (QP) mode, with a charge time of one millisecond and a discharge time of 600 milliseconds. The idea was to have a detector mode that would measure the effective interference in a communications system or, to express it in another way, measure of "nuisance value" of the interference. This mode may also be useful for scanning in frequency, where it will "stretch" short pulses to the point where they are long enough to be audible. More recently, the QP mode has become relatively unimportant. One reason is that interference limits are indicated for both CW and broadband or peak signals, and a second reason is that there are so many different communication-type signals that the QP no longer will represent a standard "nuisance value."

The detector function must be considered if X-Y recordings are to be made automatically. It is obvious that if the receiver is tuned through a CW signal fast enough, the signal will not fully charge the detector in the average detector mode. The scan rate must be selected so that the largest signal to be measured will be accurately detected. The response of the recorder is also a factor in this problem. It must be fast enough to record the detector output with the required accuracy.

The final stages in the FSVM provide the readout or indication of a signal. Normally, a panel meter is the indication used, but a number of other methods are available. Headphones may be used as an auxiliary to aid in the selection or identification of a particular signal. They may also be used in the aural slideback method for measuring one signal in the presence of another. A CRT provides a useful visual method for performing monitoring and measurement functions.

The panel meter is usually an electronic voltmeter. It is a conventional VTVM-type circuit, requiring only a balance control or "zero adjust." In conjunction with this circuit, a recorder output is often provided. suitable for strip-chart recording or for the Y axis of X-Y recorders.

A video amplifier separate from other output circuits is sometimes provided to allow analysis of the detected modulation by the use of a recorder or oscilloscope.

Several areas of design require special consideration to provide necessary characteristics for FSVM's. For example, the FSVM must be carefully shielded to prevent any signal leakage through the case. The leakage paths may be either

actual physical openings, such as cracks or holes, or may be leads which penetrate the case, such as power leads. In extremely high-level fields or in strong magnetic fields, leakage may occur through the case itself, but it is more likely that leakage will be through other paths at lower levels.

The FSVM is usually a fairly compact unit, thereby making it possible to design a one-piece case free of any cracks or seams. In this way, only the mating of the front panel and the case need be made leakproof. The front panel itself offers many potential problems due to the necessity of input and power leads, control shafts, frequency dials, ventilation requirements, and the panel meter. For each of these problems, satisfactory solutions have evolved. For leads, adequate filters are available. Waveguide-beyond-cutoff techniques are feasible in some cases for ventilation purposes and for control-shaft shielding.

Another area of some interest to FSVM design is the power supply. Because stability and precision are necessary qualities of FSVM's, the power supply must be stable. If portability is desired, battery operation is usually the answer. The possibility of transistorizing all FSVM circuits for portable instruments is certainly attractive, because of the reduced battery requirements as compared to those of a similar vacuum-tube FSVM.

Because of the various special requirements discussed in the previous paragraphs, FSVM's for interference measurements must be specially designed. At the present time, there are several equipment manufacturers active in the field.

Alphabetically, these are:

Fairchild Electro-Metrics Corporation
Amsterdam, New York

Hewlett-Packard
Palo Alto, Calif.

Polarad Electronics Corp.
Long Island City, N.Y.

The Singer Company, Singer Instrumentation
(Empire Devices, trademark) Bridgeport, Conn.
(EMC Instrumentation, trademark) Los Angeles, Calif.
(Stoddart Electro Systems, trademark) Los Angeles, Calif.

Some FSVM's are listed in Table 17-2. Several of the listed instruments will be recognized as plug-in units for a basic receiver. These units are for Empire NF-105 and NF-112 systems and the Polarad FIM-2. The plug-in units are listed separately if their status varies with each specification. The Polarad CFI uses plug-in units corresponding to those used with the Polarad FIM-2, but are not listed separately since each unit has the same status. A similar situation exists with the Empire NF-205, which uses units corresponding to those of the NF-105. Each of the equipments listed is available with a wide range of accessory equipment and pickup device.

Frequency Range	Instrument
20 Hz – 15 kHz	Empire NF-315
30 Hz – 15 kHz	Stoddart NM-40A
20 Hz – 50 kHz	Fairchild EMC-10
10 kHz – 110 MHz	Hewlett-Packard HP-8553
10 kHz – 250 kHz	Stoddart NM-12AT
14 kHz – 1 GHz	Fairchild EMC-25
14 kHz – 250 kHz	Stoddart NM-10A
15 kHz – 150 kHz	Empire T-X/NF-105
150 kHz – 30 MHz	Empire T-A/NF-105
150 kHz – 32 MHz	Stoddart NM-25T
150 kHz – 1 GHz	Empire NF-205 (4 plug-in units)
150 kHz – 32 MHz	Stoddart NM-22A
500 kHz – 1.25 GHz	Hewlett-Packard HP-8554
20 MHz – 1 GHz	Empire NF-105 (3 plug-in units)
10 MHz – 40 GHz	Hewlett-Packard HP-8551
20 MHz – 400 MHz	Stoddart NM-30A
30 MHz – 1 GHz	Stoddart NM-37/57
375 MHz – 1 GHz	Stoddart NM-52A
1.00 GHz – 10.0 GHz	Polarad FIM (4 plug-in units)
1.00 GHz – 10.0 GHz	Stoddart NM-65T
9.85 GHz – 15.35 GHz	Polarad FIM-KS
14.80 GHz – 21.0 GHz	Polarad FIM-KU
1 GHz – 10 GHz	Stoddart NM-62A
1 GHz – 10 GHz	Empire NF-112 (4 tuning units)
10 GHz – 15 GHz	Empire T-5/NF-112
15 GHz – 21 GHz	Empire T-6/NF-112
1 GHz – 10 GHz	Polarad CFI (4 tuning units)
1 GHz – 26.5 GHz	EMC Instrumentation EMA-10

Table 17-2. Frequency-Selective Voltmeters

Spectrum Analyzers For Interference Measurement

Spectrum analyzers are useful as calibrated receivers or frequency selective voltmeters in the measurement of EMI. Swept frequency techniques are especially well suited to EMI testing because signals sometimes appear at frequencies unknown to the operator of the measurement device. Since large frequency ranges are continuously scanned, interference signals are not likely to be missed.

Measurements in shielded enclosures require positioning pick-up devices for maximum readings. With swept frequency receivers, this may be readily accomplished, and reflections or "holes" can be easily located.

Significant amounts of time can be saved in all stages of the EMC program through the use of swept frequency techniques.

Spectrum analyzers are available over the full frequency range from 20 Hz to 40 GHz. Sensitivity and accuracy are equivalent to hand-tuned receivers. Therefore, all measurements that require an EMI meter can be made with a suitable spectrum analyzer. Spectrum analyzers are especially well suited to measuring radiated and conducted emissions.

Methods

Measurement techniques are similar to traditional methods used with hand-tuned meters. One exception is that detector mode is not selectable. Peak detection is used almost without exception in spectrum analyzers. The method for making each measurement can be broken into three phases:

1. Calibration: Spectrum analyzers are available that are calibrated directly in dBm, dBμV, or voltage throughout their frequency range. If the particular unit in use is not calibrated in absolute amplitude, a signal generator can be used as a transfer device.

A signal generator with a known output is connected to the spectrum analyzer, and the signal is adjusted to a convenient reference. Then, because the CRT is calibrated in dB, the amplitude of any signal appearing can be read directly. This assumes a flat frequency response, but spectrum analyzers are usually quite flat across wide frequency ranges.

Calibration with an impulse generator is unnecessary because the impulse bandwidth of the spectrum analyzer can easily be measured from the CRT presentation of a CW signal. Each bandwidth used can be measured and recorded. A constant correction can then be added to change signal levels read to broadband spectral intensity.

2. Measurement: When calibration is completed, measurements can be taken by adjusting the spectrum analyzer to scan the frequency range of interest using the calibrated scan controls. For example, if one wished to measure signals in the 20 kHz -- 50 MHz range, he would probably scan from zero to 1 MHz in one sweep and from zero to 50 MHz in one sweep to obtain the necessary frequency resolution at the lower frequencies. This would be done by setting the scan width (or dispersion on some analyzers) to 100 kHz per division, and using a center frequency of 500 kHz to obtain a 0-1 MHz scan. The analyzer will gen-

erate a zero frequency indicator (actually the first L.O. feedthrough) that will aid in making accurate frequency measurements. Similarly, a 0-50 MHz scan can be obtained b using a 5 MHz per division scan width and a center frequency of 25 MHz.

Once the proper scan is obtained, it is necessary to identify signals on the CRT as real or spurious, and broadband or narrowband.

This is done in two steps. First, 10 dB of input attenuation is added. If all signals on the CRT drop by 10 dB, they are real. If any signal drops more than 10 dB, it is spurious. Input attenuation is added until all signals drop 10 dB for 10 dB added attenuation. To identify broadband signals, the spectrum analyzer bandwidth is changed. If any signal changes amplitude by 20 dB as the bandwidth is changed by a factor of 10, it is a broadband, impulse type signal. CW signals will retain a constant amplitude. The broadband correction factor will apply to any signal which is found to be impulse in nature.

3. *Data Recording:* The data from a test can be recorded by several means. The conventional point-by-point recording of signal amplitude, frequency, and correction factor may be used. However, this takes a large amount of time that could be spent in data reduction.

CRT photos can be used to record the signal levels throughout a given frequency range. In this method, a graticule overlay can be prepared in advance with specification limits superimposed. The probe or antenna factors can be included in the specification limits as can the bandwidth factor for broadband signals. The photos will then show a comparison of interference levels with specification limits.

A third method is to use an X-Y recorder to record interference levels. All necessary outputs are provided by the spectrum analyzer, and the X-Y recorder can be accurately calibrated in amplitude and frequency. X-Y charts similar to the CRT overlays previously discussed can be prepared so that all the important information is available on one hard copy.

Accuracy Considerations and Capability

Accuracy can generally be considered to be composed of two parts: frequency accuracy and amplitude accuracy.

Amplitude accuracy usually depends on the following terms: flatness, display linearity, absolute calibration uncertainty, and gain (attenuator) accuracy. Overall accuracy of ±2 dB without special methods is not uncommon. IF substitution techniques can considerably improve overall accuracy by eliminating flatness and display errors. X-Y recording will eliminate the inaccuracies introduced by display non-linearity.

Frequency accuracy depends mainly on the accuracy of the scan width. Crystal markers or digital counters can be used to increase accuracy, but are usually unnecessary for meeting MIL-STD-461 testing.

Sensitivity for CW signals is on the order of −15 dBμV for most spectrum analyzers in the 0-1 GHz range. Above 1 GHz, CW sensitivity drops off with frequency but remains better than +10 dBμV to 18 GHz for some analyzers. Narrow bandwidths give highest CW sensitivity.

For broadband signals, wider bandwidths give highest sensitivity. This is because the spectrum analyzer noise level is basically white noise, which increases 10 dB for a factor of 10 increase in bandwidth, while the impulse noise of the interference source increased 20 dB for a factor of 10 increase in bandwidth. Typical sensitivities are on the order of +25 dBμV/MHz for frequencies less than 1 GHz. At 18 GHz, +55 dBμV/MHz or better is obtainable. Amplifiers will help over the full range, so sensitivity is not a serious drawback.

Spectrum analyzers in the microwave region use harmonic mixing processes to obtain the high frequency coverage. Because image and multiple responses may be generated, and because signal identification is difficult on broadband signals, tracking preselection is necessary for all harmonic mixing spectrum analyzers. This is the only way to eliminate both image and multiple responses. The bandwidth of the front end is also reduced, minimizing spurious responses and broadband overload.

For lower frequency analyzers where harmonic mixing is not used, there is no signal identification problem. Fixed band-reject filters may be used to prevent broadband overload, however, if specific regions of the spectrum have unusually high interference levels. For example, power lines often have high interference levels at the low frequency end of the spectrum. To eliminate overload while making measurements at higher frequencies, a high pass filter can be used.

Spectrum analyzers are also available with CRT displays that allow storage of signal traces by various persistences of the CRT phosphor. These prove extremely useful for transient phenomena and CRT photography. Another feature available allows easy sweep-testing of filter response versus frequency. A sample of the spectrum analyzer swept oscillator is applied to a heterodyning signal generator. The signal generator then supplies the input to the filter under test while the spectrum analyzer traces the output response.

Antenna return loss, amplifier gain, and many other frequency-dependent functions can be measured over a wide dynamic range with the spectrum analyzer used as a frequency selective voltmeter.

Signal Generators

Signal generators fulfill two types of requirements in interference measurement: they provide signals for substitution-type measurements, and they provide signals for susceptibility testing. For two reasons, the subject of signal generators will be discussed only briefly here: first, it is a broad field about which a book could be written, and second, it has been one of the major areas of concentration in the instrumentation business for a number of years. Therefore, only items of significance to interference testing will be discussed here.

A signal generator, in the simplest analysis, generates a voltage at a particular frequency. But this voltage and frequency have many properties, most of which are significant to interference tests.

The signal levels required for interference tests range from a fraction of a microvolt to many volts and are usually referenced to a 50-ohm source. The microvolts will be used for substitution measurements, while the volts are for sus-

ceptibility tests. In each case, the levels should be known to an accuracy of at least ±2 dB. The only problem in obtaining the low-level output is generator leakage. The generator should be shielded as completely as the FSVM. In this case, however, it is to ensure that the only signal coming out of the generator is at the output attenuator terminal.

The higher levels required present more of a problem when they stipulate levels of +30 dBm (1 watt) or so for the radiated susceptibility measurements from 25 MHz to 1000 MHz. The nominal output of most generators in this range is about 0 dBm (1 milliwatt). The problem is not a state-of-the-art situation, but rather one of economics.

At these higher voltage and power levels, most users have been satisfied with oscillators, which are generally unsuitable for interference testing for at least two reasons: they have a high harmonic content relative to generators, and it is often impractical to scan them in frequency. Since much susceptibility testing must be done by scanning, oscillators are ruled out. Harmonics often are a severe problem during receiver susceptibility tests, which is another reason oscillators are not suitable. As a result of the relatively light demand, there are few sources of high-level signals.

Output levels are usually adjusted manually or by switching a direct-reading attenuator. This method appears to be satisfactory, as is the accuracy of the attenuators. When higher power sources are available, the design of attenuators will be more difficult but still feasible.

The variation in output level as frequency is changed creates another time-consuming problem. Some of the newer generators have been improved so that they are truly flat, but for most of the frequency range, constant readjustment of various dials is necessary to maintain a given level.

Frequency stability is a classic requirement for signal generators and one that is also necessary for interference work. Fortunately, it is usually met. Frequency range is another matter. At least eight different generators are needed to cover the frequency range between 30 hertz and 10 GHz. Depending on the generators used and the levels required, a number of amplifiers will also be required. This large number of equipments that must be handled and inter-connected makes susceptibility testing time-consuming and costly.

It is apparent that the ultimate signal source is not available, nor will it be soon. For the present, the interference test planner must "make do" with what is available and take advantage of new developments in signal sources as they occur.

Test Accessories

In addition to frequency-selective voltmeters and signal generators, there are other interference-testing instruments that are not used in other areas of electronics instrumentation. These include line impedance stabilization networks (LISN's), current probes, transient generators, and equipment for the power-line conducted-susceptibility test.

LISN's have been used to perform conducted interference and susceptibility tests. They are simple networks that are inserted in power leads to offer something approaching a standard impedance to the RF currents from the test sample.

They are usually built in aluminum boxes and provide connections for the power line in and out, ground connection, and a coaxial connector for the FSVM. The design recommended in a number of interference specifications uses a 5-microhenry coil and is suitable for use from 150 kHz to 25 MHz. Over this range, the impedance varies from about 5 ohms at 150 kHz to 50 ohms at 25 MHz. The LISN is not usable much above 25 MHz because of stray impedances. Objections to the use of this device are becoming more pronounced. One is that while it does furnish a standard impedance it is not the impedance seen in the normal installation. Another objection is its limited frequency range. However, the LISN will probably continue in use for the foreseeable future.

The method that some authorities feel should supplant the LISN is the current probe. These devices, which are essentially current transformers such as those used by clamp-on ammeters, are available in several configurations suitable for use from audio frequencies to 1 GHz. They are used as pickup devices for the FSVM. Because the LISN helps provide a voltage measurement, and the current probe a current measurement, neither alone will completely describe an RF signal in a line.

Additional instrumentation and accessories are required for many interference tests: rejection filters, high- and low-pass filters, couplers, terminations, oscilloscopes, cameras, and other monitoring devices. Generally, however, these equipments are fairly standard and need not be specifically designed for interference work.

CALIBRATION AND CERTIFICATION

It is apparent, after considering some of the instrumentation used for interference tests, that any laboratory or group engaged in interference measurements must have available for use a considerable inventory of equipment, both standard and special. To manage and maintain the equipment efficiently, a formal maintenance, calibration, and certification program is a necessity. In this context, maintenance refers to the overall repair work on equipment, while calibration refers specifically to verifying that an instrument performs to its specifications. Certification is the formal declaration, in one form or another, that an instrument has been examined and found to meet its specifications. The certification may be indicated by a small tag on the instrument with the date of certification and the certifier's name.

The operation or use of a calibration facility is well known to any laboratory or group using electronic instrumentation. Whether the group performs its own calibrations or uses the facilities of commercial calibration laboratories or the services of an instrument manufacturer, most users recognize and appreciate the need for periodic calibration of electronic instrumentation.

To discuss all phases of a calibration facility would require several volumes, so the material here will be limited to mentioning the necessities for calibrating FSVM's and signal generators, which comprise the majority of the instruments used in interference work.

To check a signal generator, the basic requirements are a frequency meter and an output indicator. The frequency meter requirement is amply fulfilled by

an electronic counter with appropriate transfer devices to permit accurate frequency measurements of any required frequencies. The output indicator can be a power meter of the caloric type or, more commonly, of the bolometer type. The usual range for the bolometer power meter is from about −30 dBm to +10 dBm. The upper working range can be extended by using standard attenuators. The bolometer power meter can check the output level over this range of levels and from frequencies of 10 MHz and up. The upper frequency point is limited only to available bolometer mounts and is of the same order as that of available FSVM's. To check the output attenuator of the signal generator at levels higher than the maximum power meter level, a set of standard barrel attenuators can be used in conjunction with the FSVM.

The FSVM can usually be checked adequately with a standard signal generator. The absolute levels cover the same range, and the accuracy of the generator frequency and level are usually sufficient to verify proper operation of the FSVM. The attenuator in the FSVM should be checked at several frequencies, and the over-all absolute accuracy should be checked at several frequencies in each band. There should be an annual verification of calibration of the various accessory items used with the FSVM, such as antennas, current probes, LISN's and related equipment. There should also be quarterly tests and verification of condition of cables and connectors.

In some situations, an actual calibration may not be possible or necessary, but still an indication of proper operation is desired. In these cases, the unit can be compared to a similar unit, if available, or a spot check or two may be made using a signal generator or other known source.

Adequate and capable maintenance and calibration of the equipment used for interference tests is necessary to obtain good data and will also improve the attitude and morale of persons using the equipment.

MEASUREMENT TECHNIQUES

METHODS AND PROCEDURES

Because of the wide variety of equipment that can be subjected to interference tests, there will be a correspondingly wide variety of test setups. In many instances, the tests will be performed in some form of shielded enclosure, with the equipment on a bench, if it is small enough, or in a rack or cabinet. In other cases, equipment will be tested "on location." For these reasons, there is no single prescribed test setup. Each EMI specification provides guidelines that enable the test planner to design an appropriate setup for the equipment under investigation. Several problems the test planner must consider are discussed in the following paragraphs.

If the unit under investigation is fairly small, such as a conventional radio receiver, it will be located on a bench in a shielded enclosure. The bench will normally have a copper top bonded to the wall of the enclosure. The equipment

will probably be connected to the bench top unless it is portable equipment normally operated without a ground.

One philosophy followed by most EMI specifications concerns the method of operating the unit under test. This is that the unit shall be operated so as to produce the highest levels of interference during radiated and conducted interference tests; and during susceptibility tests, the unit shall be operated so as to produce maximum susceptibility. This philosophy is prevalent throughout the EMI field and some have dubbed it the "worst case" philosophy. Situations arise where the number of variables in the operation of a unit would require an unreasonably high number of tests. In these situations, it is easy to see how useful the "worst case" philosophy can be. The effect of each variable can be considered in the test planning stage and fixed to produce maximum emanations or susceptibilities. Then, only those variables whose effect is not clear must be examined experimentally during the interference test.

Setup difficulties often arise when auxiliary units that are not to be tested are required to operate the unit under test. These auxiliary units include power supplies, signal generators, exercise equipment, monitoring equipment and loads. It is necessary to ensure that the auxiliary units do not emit EMI themselves, and that the auxiliary units substantially duplicate the normal operation and configuration (including cables) of the equipment under test. Several frequently encountered situations concerning power supplies, exercise equipment, and monitoring equipment will be discussed briefly.

Units using self-contained batteries obviously require no special considerations insofar as power sources are concerned. Units normally operating from an AC line must be provided with an interference-free source. This source is available in a standard shielded enclosure but is virtually impossible to achieve elsewhere due to the propensity of AC lines to act as antennas.

If 28 VDC is required, it is usually furnished for functional testing by an AC-to-DC converter. However, some types of these converters can be significant sources of interference themselves and are therefore unsatisfactory as power sources during interference tests. If a shielded enclosure is used, the converter may be located outside the enclosure, and the DC power fed into the room through suitable isolation filters. Or batteries may be used if they can supply enough power.

In some instances, a unit may require a number of signal or control voltage inputs to achieve normal operation, such as an airborne digital computer unit used in navigation. This type of unit will often have a companion unit termed a "test set" or exercise unit, designed as a developmental or functional testing unit but not necessarily complying with the same EMI specification limits as the airborne unit. The problem is to achieve complete and normal operation of the airborne unit without having the companion unit affect the interference measurements. Again, a possible solution to this problem is to locate the companion tester outside the shielded enclosure and introduce the exercise signals by means of feedthrough fittings and shielded coaxial cable.

Auxiliary monitoring equipment may be required during interference tests either to ascertain normal operation of a unit or to note susceptibility, or per-

haps for both purposes. As previously discussed, care must be taken to prevent any signal from the monitoring equipment from affecting the measurement. Indicating meters, either electrical or electronic, may cause no problem, but such equipment as oscilloscopes and electronic counters may. The sweep circuits in the former and the counting and oscillator circuits in the latter, if not properly shielded or otherwise contained, are significant sources of interference. Here again, the solution may be to locate the monitoring equipment outside the shielded enclosure, or perhaps to devise other methods of monitoring.

To illustrate some of the problems discussed, several aspects of an actual test setup will be mentioned. The equipment being tested for radiated interference was a missile guidance receiver and its associated beacon transmitter. The system was in three packages: receiver, transmitter, and control unit. These three units were positioned on a shielded room bench, properly interconnected, and attached to their associated test set by a large umbilical-type cable and one X-band flexible waveguide.

Preliminary interference measurements showed that the test set produced more EMI in some frequency ranges than did the guidance equipment, making it desirable to remove the test set from the screen room. However, this required several substantial changes in the test setup, because the test set supplied DC power, RF test signals, and monitoring functions.

The requirement for DC power was met by the use of a battery cart that supplied DC power from lead-acid storage batteries and included its own charger. This arrangement provided noise-free DC power during tests and convenient recharge capability between tests.

The RF signals were normally coupled between the test set and the guidance equipment duplexer by means of flexible waveguide. To provide the isolation necessary while still using the RF signals from the test set, an arrangement was designed to permit the signals to enter and leave the screen room via a "link." This link consisted of two horn antennas, one mounted inside the room and the other outside, each facing the other. Between the horns was a standard pipe nipple, commonly used to permit power line entry through the screen room wall, but in this case serving as a circular waveguide. The cutoff frequency of the nipple was just below X-band, so no serious violation of the screen room occurred. The horn antennas and the test set outside the screen room and the missile equipment inside were connected by the flexible waveguide. Figure 17-4 shows a plan view of the final setup. The umbilical cable carried about 40 leads, including control outputs from the guidance set and telemetry outputs for monitoring in the test set. For this umbilical cable, a unit was constructed that provided the correct termination for each lead in the cable. The termination unit was then located on the shielded room bench.

Since removal of the umbilical precluded monitoring during tests, with the exception of the RF signal, the following procedure was used to verify proper operation. A complete checkout was performed using the normal umbilical. Then the test proceeded with the terminated umbilical and only the RF signal indicating proper operation. After an interference test was completed, the checkout cycle was rerun and if proper operation was indicated, it was concluded that no

malfunction had occurred.

In general, test setups should be thoroughly engineered during the planning stage. All the requirements of the applicable specification can then be considered in detail, and special interpretations can be sought where required. Special jigs and fixtures such as the umbilical termination unit, the waveguide horn antennas, and the battery cart can be prepared or obtained with no loss of time.

Two categories of radiated measurements are usually made during interference measurements. These are the levels of radiated signals from the test sample and the levels of signals that cause the test sample to malfunction. Many of the problems encountered during these measurements are common to all radiated measurements, so both types will be discussed in the following paragraphs.

One of the more impressive aspects of these tests is the wide frequency range considered, usually 15 kHz or 150 kHz to 10 GHz or higher. While the interference-oriented engineer is probably not awed by this range, the equipment designer may be somewhat impressed. This wide frequency range requires a great variety of equipment and techniques to provide signal sources, receivers, and antennas, as well as to perform the measurements.

A comprehensive definition of the near field is difficult, and may be controversial. Roughly speaking, the near field will extend approximately 3 wavelengths from an antenna whose size is small compared to a wavelength, or to $2D^2/\lambda$ (where D is the maximum antenna dimension and λ is the wavelength of interest) for an antenna whose size is comparable to a wavelength or whose size is many wavelengths. This relationship is shown, normalized to wavelengths, on the graph Figure 17-5. Not until the frequency reaches several hundred megahertz does the $2D^2/\lambda$ criterion give a 1-meter measurement distance (often used in interference measurements) outside the near field. Even there, if the sample size were large, the measurements would still have many aspects of near-field work. Both these requirements must be satisfied.

As an example, consider an antenna one wavelength long at 30 MHz. The wavelength, λ, at 30 MHz is 10 meters. Thus the 3λ separation criterion requires a 30-meter separation, which dominates the $2D^2/\lambda$ criterion of 20 meters. At the second harmonic, however, $3\lambda = 15$ meters and $2D^2/\lambda = 40$ meters. Thus, at the lower frequencies, the 3λ separation is the dominant criterion, but at higher frequencies, the $2D^2/\lambda$ criterion begins to dominate.

In keeping with MIL-STD-463, "Military Standard Definitions and System of Units," the term "field strength" applies only to measurements made in the far field. The measurements may be of either the electric or magnetic component of the field. The measurements, abbreviated FS, may be expressed as V/m, A/m, or W/m^2, and any one of these quantities may be converted to the others. For measurements made in the near field, the term "electrical field strength" (EFS) or "magnetic field" (MFS) will be used, according to whether it is the electric or the magnetic field that is measured. EFS is expressed as V/m and MFS as A/m. In the near field region, the field measured will be the resultant of the radiation, induction, and the quasi-static ($1/r$, $1/r^2$, and if present, $1/r^3$) components, respectively, of the field where r is the distance from the source.

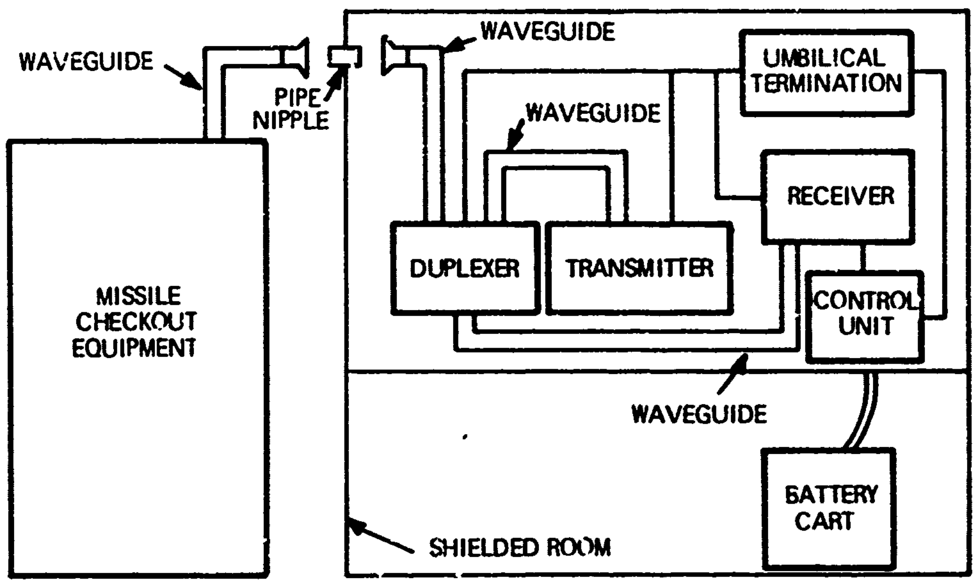


FIGURE 17-4. PLAN VIEW OF MISSILE GUIDANCE EQUIPMENT TEST SETUP.

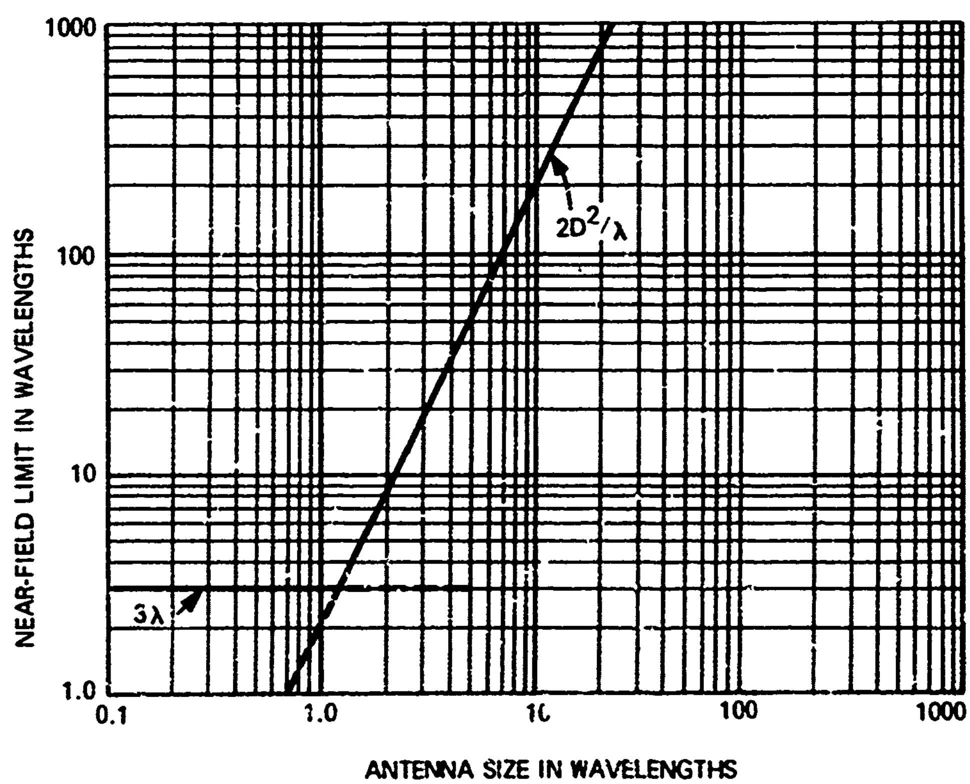


FIGURE 17-5. NEAR-FIELD REGION BOUNDARY.

The primary problem of near-field measurement is the fact that the magnetic (H) and electric (E) components of the field do not have the simple time, space, and amplitude relationship that they have in the far field. In the far field, they are in time phase, in space quadrature, and are related by the so-called intrinsic impedance of free space, 377 ohms. In the near field, the two components must be measured separately if a relatively complete picture of the radiated field from a test sample is desired. The H field must be measured by a loop antenna, and the E field by a linear antenna.

Most specifications do not require H-field measurements, however. Apparently, it has been found through experience that E-field measurements give sufficiently detailed interference information about a test sample. Loop antennas are furnished with the frequency-selective voltmeters (FSVM's) designed for interference work, so H-field measurements may be made if necessary.

The E-field measurements are usually performed to 30 MHz with a 41-inch rod positioned vertically over a small ground plane. It is important that this ground plane be as specified, because the impedance of the antenna is a function of the size of the ground plane, among other variables.

Above 30 MHz, the vertical rod is replaced by a horizontal dipole tuned to resonance at each measurement frequency. Because it is a balanced antenna, no ground plane is required. One might wonder why at 30 MHz the polarization is switched from vertical to horizontal. Actually, there is no basic theoretical reason. The signals from a test sample probably contain all polarizations, so the polarization of the test antenna is not as important as might be supposed. There is at least one specification, however, that requires orienting the antenna polarization for maximum pickup. This immediately leads into a practical problem for most test facilities, that of finding sufficient room to arrange a 35-MHz dipole vertically and still have the center of the dipole at the required distance from the test sample.

There are some new approaches to designing broadband antennas for at least part of the range (35 MHz to 1000 MHz) where half-wave dipoles have been used. These include a bowtie or thick dipole antenna and a log-periodic conical spiral. The advantage of these antennas is that they need no tuning adjustment. The conical spiral is also circularly polarized and will be sensitive to all polarizations.

Above the 1-GHz frequency, various microwave antennas are used, generally horns or horns with parabolic reflectors. Once again, the polarization problem exists, but it is not serious. In this range, there are also broadband antennas for interference measurements, specifically another log-periodic conical spiral and a parabolic reflector with a log-periodic feed. Each is suitable for use from 1 to 10 GHz.

In the actual performance of a radiated emission test, the appropriate antenna is set up either one foot or three feet or one meter from the unit under test, and connected to the FSVM. The frequency range of interest is scanned and readings are taken where signals are noted. The FSVM must be calibrated when bands are switched or bandwidth is changed. Normally, the FSVM internal cali-

bration scheme, either CW or impulse, is adequate. To be useful, the data must be reduced using appropriate antenna factors and then plotted on a graph that also shows the specification limit. Some specifications also require a measure of instrument noise at each measurement frequency to determine the absolute sensitivity of the instrument.

The performance of a radiated susceptibility test will be similar. In this case, the signal source will be connected to the antenna, and a means provided for monitoring the power or voltage supplied to the test antenna. At frequencies below 30 MHz at which a 41-inch rod is used, the test signal is essentially a voltage source because the antenna impedance will be quite high. It is usually preferable to terminate the cable to the test antenna with a 50-ohm load so the generator output meter will indicate directly the power being delivered, in this case, primarily to the termination. The actual voltage applied to the base of the antenna may be simply calculated or read from the generator dial. If high-power oscillators are used, a similar method can be used, but a high-impedance RF voltmeter must be added to monitor the applied voltage.

At frequencies above 30 MHz, the situation is somewhat simpler as the antennas used are approximately matched to the 50-ohm system. In these cases, the meter on the signal generator will indicate directly the power being delivered. For measurements that require more power than that available from standard signal generators, some power monitoring scheme is required. This can be an in-line wattmeter or a power meter used with a directional or other type of coupler.

The general term "conducted measurements" includes conducted emission and conducted susceptibility tests (except for transients) on both power lines and signal lines. Two different pickup devices are used for the tests: line impedance stabilization networks (LISN's) and current probes.

The LISN furnishes a repeatable impedance at radio frequencies to the power line so that the signals from the test sample can be measured with some precision. The network was developed for use from 150 kHz to 25 MHz and is not suitable for use outside this range. It is used in a test setup by insertion in an AC or DC power lead, with its case connected to the test setup ground.

The current probe, on the other hand, furnishes a current measurement. Generally, it will require no alteration of the cables to be measured, unless individual leads must be separated for separate measurements. While it normally will not affect the circuit to be measured, the test planner must be cautious about its use on sensitive signal lines of low impedance at which the series impedance of the probe may cause an appreciable change in the over-all circuit impedance.

An advantage of the current probe, in addition to the fact that it does not require insertion into the circuit, is its wide frequency range (from 30 hertz to 1 GHz in several probes), permitting measurements beyond the 25-MHz limit of the LISN.

As has been mentioned several times, susceptibility testing is not as highly developed as emission measurement, and many of the techniques are fairly new. The conducted susceptibility tests can be divided into two areas, RF and audio.

The RF test is relatively straightforward, using the same LISN's previously described as the coupling device from signal source to power line. Usually, the susceptibility limit is specified as a voltage or power level, assuming the LISN is a 50-ohm load. This assumption is true only over a limited frequency range of approximately 5 to 25 MHz. Below 5 MHz, the impedance of an LISN drops to approximately 5 ohms at 150 kHz. Since all LISN's have this characteristic, meaningful and repeatable susceptibility tests are possible in spite of the mismatch. Above 25 MHz, the tests will be subject to some uncertainty since the impedance of the LISN is not specified. A specific test using a specific LISN should be repeatable, but similar tests on similar equipment with a different LISN may not be, due to variations in LISN impedance above 25 MHz.

The audio portion of the test requires a more complex setup but is also a better designed test. The device used to couple the test signal to the line is a current transformer specially designed for this use. Enough signal current must be coupled into the line to cause several volts of test signal (the exact level depends on the particular specification) to appear across the input of the test sample. To accomplish this, an audio amplifier of approximately 50 watts capacity is used to drive the current transformer. The signal voltage is monitored by an oscilloscope or VTVM.

A useful aid to monitoring the signal voltage on an AC line is a variable phase shifter arranged in the test circuit to null out the line frequency as far as the monitoring device is concerned. This permits a direct measurement of the audio signal voltage either on the oscilloscope or on the VTVM.

One test for power-frequency inductively-coupled susceptibility to be performed on signal lines requires the application of a current from 5 to 30 amperes to a test wire parallel to and 2 inches away from the signal line. The product of the test wire length in feet and the current in amperes must be 60 ampere-feet. The test wire is placed successively in two positions 90 degrees apart, and at each position both 60 and 400 hertz must be used. The current can be adjusted with a standard variable autotransformer.

Transient susceptibility testing is another relatively new susceptibility test developed because of the need for flawless performance of unmanned systems and because of the vulnerability of transistor circuits to transients. A vacuum tube could endure surprisingly high transients without damage, but a transistor will often be destroyed by a transient whose peak exceeds the voltage or current rating of the transistor. The test is required only by the more recent specifications and standards.

Broadband and CW measurements must be made at the antenna terminals of receivers and of transmitters in the key-up and key-down conditions. The purpose of the measurement is to determine the level of undesired signals emanating from the test sample by this path.

The receiver tests and the transmitter key-up tests require only an FSVM or spectrum analyzer, which may be connected directly to the test sample if the sample is a 50-ohm device, or through an impedance-matching coupler, if necessary. The required frequency range must be scanned with all controls on the sample adjusted or manipulated to produce maximum interference. Care must be

taken to avoid keying the transmitter during the measurement.

The key-down tests, while performed in the same way, are made more complex by the presence of the fundamental. Some method must be used to protect the test instrumentation from damage, and also to permit measurement at least 100 dB below the level of the fundamental. For a transmitter whose power exceeds a few watts, this requires some type of coupler and a notch reject filter. Various types of couplers can be used. Directional couplers are suitable in the right frequency ranges. Resistive, inductive, or capacitive couplers can be used, but they must be calibrated over the frequency range of interest. This frequency range must include all spurious outputs as well as the fundamental and harmonics. A block diagram showing a method of calibrating the coupler and test setup as the measurements are made is shown in Figure 17-6. The test setup is predicated on the suitability of unkeying the transmitter after each measurement to switch to the signal generator to perform the substitution measurement.

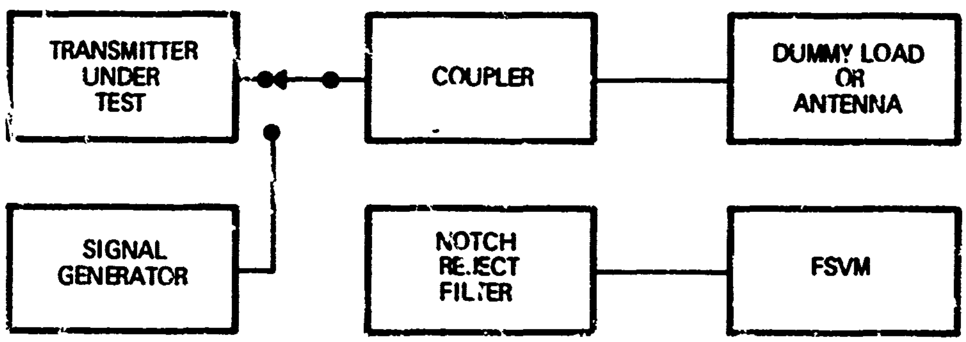


FIGURE 17-6. BLOCK DIAGRAM OF KEY-DOWN ANTENNA-CONDUCTED MEASUREMENT.

In all test setups, regardless of the coupler, it is necessary to use a reject filter. Because the filter will alter the calibration of the test setup, it must be included during any calibration procedure.

There is some argument as to whether the transmitter should operate into a dummy load or into an antenna during this test. The basis of the argument is the fact that an antenna is a band-pass filter and will actually prevent or attenuate radiation of some signals that will be present if the transmitter is connected to a dummy load. While this is a valid argument, some transmitters have no specific antenna, so the only recourse is a dummy load if repeatable measurements are to be obtained. The practical approach is to make the tests with the specific antenna when feasible and with a dummy load when not.

Certain susceptibility tests must be performed on a receiver in addition to those already noted. These fall into two categories: one-signal tests and two-signal tests. The one-signal test, referred to in most interference specifications as the receiver-input rejection test, measures the spurious response characteristics of a receiver. The two-signal tests, which can be quite complex, include cross-modulation and intermodulation measurements.

Difficulty with the one-signal test occurs because of harmonic and spurious outputs of the signal generator. For example, with a receiver frequency of 250 MHz and a generator frequency of 125 MHz, the receiver will certainly respond, due to the second harmonic of the generator. For this reason, a good low-pass filter must be used to eliminate generator harmonics. It is still possible for the receiver to respond to the harmonic-free 125-MHz signal, since the receiver will actually produce a 250-MHz signal in its input stage because of nonlinearities. This response would be one item of data desired from the test. Incidentally, microwave receivers with waveguide inputs normally would not be checked below the cutoff frequency of the waveguide, since the waveguide is an excellent high-pass filter.

The two-signal tests present the harmonic output problem as indicated above, and an even more severe problem. One of the tests, the intermodulation test, is made to determine the degree to which the receiver will produce intermodulation when two strong off-channel frequencies are present simultaneously at the receiver input. For example, if the receiver is tuned to 3 MHz, the two test generators may be tuned to 4 and 7 MHz. The levels at which the two generators produce a response in the receiver are the data desired. The difficulty usually encountered is that the 3-MHz signal may be produced elsewhere in the test setup and inaccurately included as part of the receiver data. There are several ways to combat this problem. The simplest is to place a 3-MHz notch reject filter at the input to keep the externally-produced intermodulation signal from entering the receiver. Because the external intermodulation is probably produced in the two signal generators, any method of isolating the two generators will improve the situation. It can be done with resistive attenuation if the generators have sufficient output, or it can be done by again using reject filters. In this case, a 4-MHz filter is placed at the output of the 7-MHz generator and a 7-MHz filter at the output of the 4-MHz generator. Usually, the most satisfactory approach will be to use a combination of these methods to prevent external intermodulation.

The test planner should recognize that there are many types of intermodulation. The specifications usually call for measurement of one or two different types, but others may be noticed while the setup is being adjusted. Any combination of sums and differences of the fundamentals and harmonics (the harmonics being produced in the receiver front end) may result in a receiver response. The severity of the problem will be a function of the environment of the receiver and the linearity of its front end.

Many aspects of interference testing have been mentioned briefly in the preceding paragraphs and it is easy to see why many consider this testing difficult. The range of frequencies and signal levels considered and the number of different types of tests required combine to present the test engineer with a formidable challenge both in instrumentation and in measurement techniques.

ACCURACY AND TOLERANCES

Accuracy is defined by Webster as "exactness; exclusion of error." To the accountant, an accurate statement leaves no room for error. Either the statement is in balance or it is not. Some mathematicians leave no margin for discussion when they speak of an expression, such as an equation or theorem, as being accurate. The probability expert is concerned with the prediction or description of an event within certain limits. The electromagnetic compatibility engineer is concerned with obtaining and interpreting data correct within known limits.

As in all fields of engineering, there is always some margin of error or definable amount of inexactness in any physical measurement. There are methods by which a numerical value can be assigned to the margin of error. A common method is to take the largest known error of a measured value and compare it to the magnitude of the quanity measured.

Suppose the frequency of a transmitter output signal is 1 GHz and one wishes to measure this frequency with a standard frequency meter that uses a low-frequency counter accurate to ±1 hertz in several megahertz. Also available is a heterodyne unit that enables a zero beat to be obtained between the signal to be measured and the harmonic of a signal supplied by the counter. The zero beat may be observed visually on an oscilloscope or audibly with a set of earphones. The precision with which the frequency can be measured will depend on the degree to which the zero beat can be established. There will be a finite range of oscillator tuning over which no noticeable change will occur in the zero beat pattern or signal. This range can be measured by counting the frequency with the counter at both limit points of this "twilight zone." A numerical value of the accuracy of the measurement is obtained by dividing the difference of these frequencies by their average. Symbolically, designate the frequency at the upper end of the questionable region as f_2 and the lower end as f_1; then

$$\text{accuracy} = \frac{f_2 - f_1}{\frac{1}{2}(f_2 + f_1)} = \frac{2(f_2 - f_1)}{f_1 + f_2} \tag{17-1}$$

An alternate expression is given by:

$$\text{accuracy} = \frac{\Delta f}{f_{avg}} \tag{17-2}$$

The result is usually expressed as so many parts per thousand, per million, etc. For example, suppose for one illustration that $\Delta f = 30$ hertz and $f_{avg} = 1$ GHz, then the accuracy is $30/10^9 = 3$ parts in one hundred million. This is usually expressed in a shorthand notation as $3{:}10^8$ which is read as "3 parts in ten to the eighth." Accuracies of this degree in interference testing are generally obtained only in frequency measurements.

An alternate method of frequency measurement is to use a frequency counter to make a direct count of the test sample output. Currently available frequency counters can make a direct count of frequencies up to 50 MHz, with an accuracy of 1 part per million (1 Hz per MHz) or better. Accuracy depends

largely upon counter gate timing, which in turn depends upon the accuracy of a stable crystal oscillator, usually internal. For frequencies above 50 MHz, frequency counters normally use plug-in frequency converters to heterodyne the test signal into the basic counting range. Converters for use up to 18 GHz are currently available. Oscillator injection for the frequency converter is derived from the same stabilized crystal oscillator used to control the counter gate.

For measuring the frequency of keyed or pulsed signals as well as CW signals, the frequency counter can use a transfer or proxy oscillator. The proxy oscillator is a variable frequency oscillator that can be adjusted for phase lock with the signal under test. The proxy oscillator thereby provides the frequency counter with a steady signal for counting purposes.

Frequency can be measured with accuracy not obtainable in measuring power, voltage, or current. Fortunately, in the EMI disciplines it is not often necessary to be concerned with microvolts or microamperes when measuring kilovolts and amperes.

The state of the art in instrumentation is not adequate to allow measurements of power, voltage, or current quantities to parts in 10^7 or 10^8 or greater precision. A voltmeter or ammeter with an accuracy of one percent ($1:10^2$) is a fairly standard instrument. Accuracies of one hundredth of one percent ($1:10^4$) are much more difficult to incorporate into a reasonably-priced instrument.

The unit of measurement most often encountered in EMI testing is the decibel, more commonly referred to as the dB. The dB is defined on the basis of a power ratio (or voltage ratio, if referred to the same impedance). Symbolically:

$$dB = 10 \log \frac{P_2}{P_1} = 20 \log \frac{V_2}{V_1} + 10 \log \frac{Z_1}{Z_2} + 10 \log \frac{k_2}{k_1} \qquad (17\text{-}3)$$

where:

P_1 and P_2 are power levels in circuits 1 and 2

V_1 and V_2 are voltage levels in circuits 1 and 2

Z_1 and Z_2 are the absolute magnitudes of the corresponding impedances

k_1 and k_2 are the values of power factor for the impedances

It is quite common to designate P_1 or V_1 as some particular power level or voltage magnitude. Most power measurements are based on dB above a milliwatt, or dBm.

V_1 may be chosen as 1 volt, 1 millivolt, or 1 microvolt, depending on the circumstances. These are related as follows:

1 volt = 60 dB above a millivolt (dBmv), or

120 dB above a microvolt (dBμV).

When the impedance of the measuring device is known, dBm can be converted to a voltage base. For example, on a 50-ohm system, 0 dBm is equal to +107 dBμv.

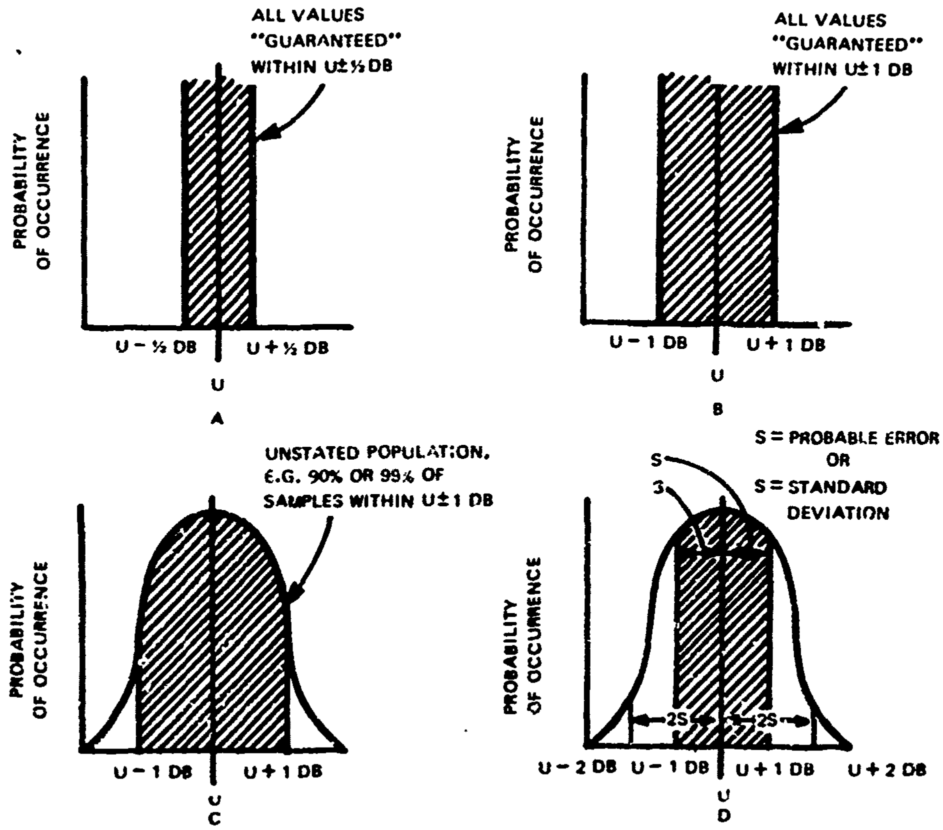


FIGURE 17-7 SOME INTERPRETATIONS OF "1 DB ACCURACY" (ADAPTED FROM ELECTRO-TECHNOLOGY, OCT. 1964, COPYRIGHT 1964 BY C-M TECHNICAL PUBLICATIONS CORPORATION).

Most data recorded in EMI tests is in dB and most common measuring instruments such as signal generators, interference-measuring receivers, and power meters are calibrated in dB. Calibration to ±1 dB is considered adequate for interference measurements. On a typical calibrated scale of reasonable size it is not practical to visually interpolate readings to any closer accuracy than ±0.5 dB. EMI measurements are usually described as being accurate to a specified number of dB. Figure 17-7 shows four different interpretations of "an accuracy of 1 dB." Suppose a set of data is described to be accurate within 1 dB tolerance. This includes the effects of the precision (or lack of it) of the equipment calibration and the instabilities that may be present in the quantity being measured. As indicated by Figure 17-7 (a), every entry of data can be in error by 0.5 dB or as much as 1 dB; in Figure 17-7 (b), the entry can be above or below the true value. The amount of deviation allowable depends upon the interpretation given to "1-dB accuracy." The indicated values may follow a log-normal distribution, in which case 1-dB accuracy means that for a certain part of the time the indicated value will be within 1 dB of the true value as illustrated by Figure 17-7 (c). In Figure 17-7 (d), for a log-normal distribution, 1-dB accuracy means that 1 dB is either the probable error or the standard deviation.

So far, this discussion has been directed at accuracy considerations involved in making actual measurements. Equally important is the determination of the degree of accuracy that is necessary. The EMC engineer should analyze the system to determine its characteristics and how they affect the measurements program.

If the output signal of a transmitter has a frequency stability of only one percent, no advantage is gained by measuring this frequency to an accuracy of $1{:}10^6$ or greater. When making susceptibility measurements, there is not much point in measuring the frequency of the test signal to any greater accuracy than is dictated by the Q of the responding circuit. When using the signal substitution method, the inaccuracy resulting from mechanically tuning the generator klystron overshadows the inaccuracies of the frequency-measuring equipment. The accuracy of frequency measurements in emission tests need not be any greater than is necessary to determine the source of the signal. One test where accurate frequency measurements would be required is the determination of the spurious response characteristics of a receiver. A spurious response may be due to a rather involved combination of frequencies inherent to the receiver, and very accurate measurement of these frequencies will be necessary if the source of the spurious response is to be identified.

In making interference measurements, the engineer could have access to instruments that would measure every parameter to $1{:}10^8$, but the resulting data would be inaccurate because of conditions in the measurement setup that caused errors. It is highly important that these sources of errors be recognized and taken into account when performing measurements. Some of these errors can result from improper test accessories or their improper use. Other errors are inherent to the system and are best handled through use of good measurement techniques.

The most common source of error is impedance mismatch. In any transmission system, maximum power transfer from one part to another occurs when the impedance of both parts is the same. If a signal traveling along a transmission line encounters a second transmission line having a different impedance level, some power is reflected back along the original line toward its source. Consequently, the power in the second line (which may contain the power monitor) will not be the actual power emitted by the source. This phenomenon occurs at every impedance discontinuity. The interference-measuring setups usually contain several different transmission parts, each of which may add to the possible error by reflecting a portion of the power at each interface.

In addition to the measurement error introduced, impedance mismatch is a serious problem in high-power systems. The power reflected appears as a reflected voltage on the line. This reflected voltage adds to or subtracts from the incident (from the source) voltage causing standing waves of alternating high and low voltage points along the line. The addition of the voltages may result in a potential sufficient to cause arcing that damages the transmission line, the source, or other auxiliary equipment in the transmission path. Voltage standing wave ratio (VSWR) is used to describe the amount of mismatch existing on a system. VSWR is equal to the ratio of the maximum voltage to the minimum volt-

age on the line.

Another source of possible error is the interference properties of the test equipment. The EMC engineer should not lose sight of the fact that a signal generator is a transmitter with a few refinements added. The output is rich in harmonics that can cause errors. For instance, when an apparent hole is found in the rejection characteristics, while performing the selectivity test on a receiver, it is necessary to verify that the hole is actually at the same frequency as the fundamental signal generator output and not at the second, third, or higher harmonic. This can usually be resolved with an appropriate low-pass filter.

The interference-measuring receiver is simply a receiver with special functions added. It is subject to spurious responses and other ills of an ordinary receiver. The input stage of an interference-measuring receiver and the output stage of signal generators are nonlinear; they are therefore subject to intermodulation product generation when more than one signal is present. In performing an intermodulation test on receivers, the products generated in the receivers are often obscured by the products generated within the signal generators. The engineer or technician must determine whether the response is a true intermodulation product of the receiver or whether it is being generated in the output stage of one of the signal generators.

ADVANCED MEASUREMENT TECHNIQUES

Signal Samplers

Before any signal can be measured, a representative sample must be obtained to apply to the detector. For low-power signals of one watt or less, the transmission line may terminate at the input jack of the measuring set. It is more likely that the engineer will want to observe the signal when it is terminated in an antenna or dummy load. A signal sampler like an in-line transmission device is necessary to direct a small portion of the signal to a measuring instrument and not interfere with the normal working conditions of the device under test. Although an antenna is a signal sampler, the discussion presented here will stress in-line signal samplers.

Some of the desired characteristics of an adequate signal sampler are intimated in the previous paragraph. The output signal must be a true representation of the original signal or it is worthless, and the sampler must not couple so tightly to the main signal as to destroy its integrity, yet the coupled output must be of sufficient magnitude to be measured. The coupling must not be too large or the power handling capabilities of the measuring equipment and accessories will be exceeded, and the impedance of the main line of the sampler must be compatible with the original transmission line.

Four devices and techniques for sampling a signal will be discussed in this section. These are directional couplers, magnetic or electric field probes, resistive samplers, and high-power attenuators.

The directional coupler is the most common sampling device and may be obtained readily for frequencies above 250 MHz.

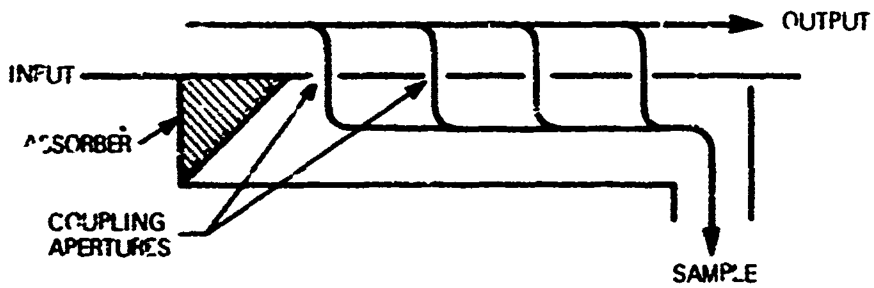


FIGURE 17-8. OPERATIONAL DIAGRAM OF THE DIRECTIONAL COUPLER.

Operation of the directional coupler is schematically represented in Figure 17-8. The coupling apertures are designed so that the forward-traveling signal is coupled into the secondary line in the following manner: The size and spacing of the apertures are chosen so that components of the forward wave add together in the secondary line. At the same time, components of a reverse-traveling wave that couple into the secondary line and reflected portions of the forward-coupled signal are absorbed in the loading material in the terminated end of the secondary line.

The degree of discrimination against backward traveling waves is called the directivity of a coupler and is expressed in dB below the coupled signal. The coupling factor of the sampler denotes the level of the signal sample in dB below the input level. Both qualities are important in EMC testing. The directivity of the coupler is important in performing tests that measure the output of a transmitter. Depending upon the degree of mismatch of the transmitter load (antenna or absorptive termination), reflections will occur. These reflected voltages are indistinguishable from the desired signals in their effect on the signal detector, and they result in erroneous indication of the transmitter's output power. Discrimination against these reflected signals is provided by the directivity of the coupler.

The coupling value should be chosen to provide maximum versatility when used in an integrated measurement system. An example will illustrate the approach to selecting the appropriate coupling of a sampler. The coupling value must be selected in accord with the maximum and minimum power levels to be measured. The minimum levels are established by the particular specification being used; the maximum power levels depend upon the particular equipment being tested.

Suppose, for a particular series of tests, that the majority of transmitters to be measured have power output levels between 1 watt and 10,000 watts. The coupling must be small enough to prevent damage to the measuring instruments and large enough to allow measurements to the limits of the specification with the sensitivity available. The minimum coupling is selected by considering the measurement of the minimum required level with the available sensitivity. For the example under consideration, the minimum signal level to be measured is -50 dBm (+30 dBm -80 dB = -50 dBm). If the minimum detectable signal level (MDL) that can be measured on the measuring instrument is -90 dBm, a 40 dB margin is

available. If a signal level at least 10 dB above the MDL is necessary for sufficient accuracy, the minimum coupling is 30 dB. With a maximum level of 10,000 watts (+70 dBm) and 30 dB of coupling, the coupled power level would be 10 watts, which might be damaging to the measuring equipment. Therefore, it would be advisable to follow the coupler with a 10-watt, 10-dB attenuator when making measurements on the high-power units. For this particular series of tests covering the above mentioned transmitter power ranges, a 30-dB coupler would be optimum. Under a different set of circumstances, a different coupling value would be chosen.

The directional coupler is a valuable tool in interference testing. There are a number of tests in which couplers are important; the most obvious of these is in measurement of the power output of a transmitter. The frequency of the output signal can be measured simultaneously to determine the frequency stability. The power output might be monitored and recorded for an extended time to determine the amplitude stability of the transmitter. Because the coupler supplies a faithful replica of the monitored signal, the sampled signal can be examined as to its amplitude characteristics for AM systems, its frequency deviation characteristics in FM systems, or the spectral characteristics in pulsed systems.

To simply monitor a signal, the coupler would be used as shown in Figure 17-9. The measuring device can be a power meter, frequency meter, interference measuring set, spectrum analyzer, deviation meter, or whatever the particular test requires. The coupler supplies a sample at a known number of dB down from the transmitter output.

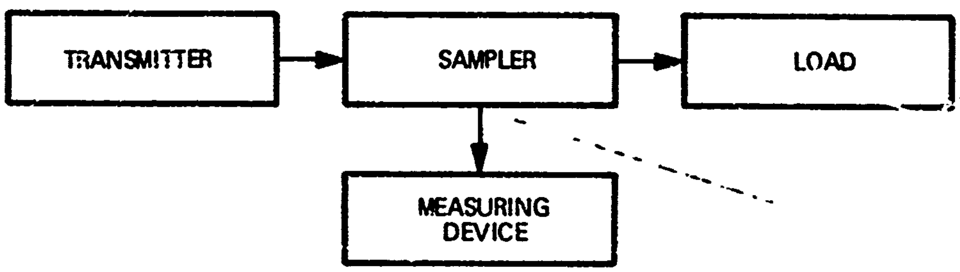


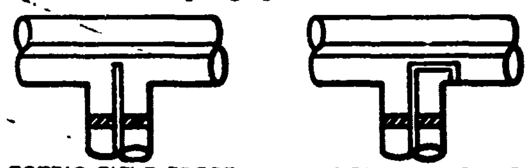
FIGURE 17-9. USE OF THE DIRECTIONAL COUPLER.

Directional couplers typically cover a 2:1 range of frequencies. Outside of their prescribed band, the parameters become erratic and the coupler should not be relied upon in these regions. Sometimes measurements will be desired at points outside the range of the coupler. To avoid having to interrupt the testing and exchange one coupler for another, which may be highly inconvenient or unwise, couplers covering overlapping frequency ranges can be operated in tandem. This is particularly desirable in a semipermanent setup designed to test transmitters whose fundamental output signals lie over a broad frequency range.

The power-handling capabilities of directional couplers are important because this limitation affects the techniques of measuring high-power signals. The power rating (main line) of the typical coaxial version of the directional coupler

is typically 1 kW, which is less than the capability of the transmission line. Greater power-handling capability can be obtained in narrow-band units. A high-power transmitter would require a narrowband coupler for that particular unit. For this situation, measurement of the transmitter harmonics is complicated, since it is difficult to sample the output at the harmonic frequencies. Measurements of the radiated field may be the only recourse.

Waveguide directional couplers are not severely limited in their power capabilities. Narrow-wall couplers, which are in the wall of smaller dimension, have the same power capabilities as the waveguide itself. These couplers experience greater variation of coupling over a waveguide band than do broad-wall couplers, but the broad-wall couplers suffer a degradation in power rating from the regular waveguide. This degradation results from voltage breakdown, which is encouraged by the wall discontinuities of the coupling apertures.



a. ELECTRIC FIELD PROBE b. MAGNETIC FIELD PROBE

FIGURE 17-10. TWO TYPES OF PROBES FOR SAMPLING A FIELD INSIDE A TRANSMISSION LINE

Probe-type samplers sample the magnetic or electric fields inside a transmission line as shown in Figure 17-10. These samplers are frequency-sensitive because they depend upon reactive effects for their operation. They are bidirectional, since power can be coupled in from the auxiliary arm as easily as from the main line to the auxiliary, but the samplers are useful in intermodulation tests in which it is necessary to apply two signals to the same line. Because of their frequency-sensitive coupling characteristic, the secondary arms should be movable to permit variation of the coupling. These probes are sensitive to loading variations on the main line that vary the electric and magnetic field configurations, resulting in alteration of the field magnitudes at the probes. They do not have uniform coupling over a very wide frequency range and hence must be accurately calibrated at each test frequency and for each different probe position used. They are not as versatile as directional couplers but they are necessary in certain testing situations.

A high resistance in parallel with the transmission line can be used as an effective sampler. This technique is useful at frequencies below about 250 MHz where field probes do not permit sufficient coupling and where directional couplers become too large. This region fortunately coincides with the frequency range where conventional resistors can be used.

One final sampling technique is the use of a high-power attenuator. The main signal is absorbed by the attenuator, effectively a load, and a small amount of power is coupled out for sampling. The chief disadvantage of this technique is that for very high-power signals the physical size of the attenuator becomes unreasonable for use in a testing program. Also, high-power attenuators are generally limited to narrow-band frequency coverage.

Dummy Loads

A dummy load is a device of appropriate impedance used to terminate a transmission line and absorb the incident power with minimum reflections. For EMI measurements, dummy loads are desirable for two purposes. First, they are necessary to terminate the RF terminals of equipment for which the proper antenna is not available or is inconvenient to use. Second, they may be used to achieve more repeatable results since their impedance characteristics are generally less erratic than those of antennas.

Any substance that will absorb electromagnetic energy can be used to construct dummy loads. Various solid materials or compositions such as barium titanate and carbon or metal powder suspended in a binder, are useful as low- and medium-powered loads. The characteristics of the material and the configuration of the absorbing element determine the frequency characteristics of the termination. Low-power loads, not to exceed 10 or 15 watts, are available to cover from DC to 10 GHz with not more than two units required. The dissipation of large amounts of power in a solid load is hampered by the difficulty of heat removal. Inefficient heat removal results in excessive temperatures that can permanently damage the absorber. Heat capacity can be increased with a larger volume of absorber or by an oil bath, but this action results in dummy loads that are impractical for testing purposes because of their physical size and weight.

As the frequency coverage is increased, the amount of power that is easily absorbed decreases. Loads are available to dissipate 10 kW average power in the VHF, UHF, and low microwave frequency regions.

Liquids and gases may be used to absorb RF energy. Water makes an efficient absorber at certain frequencies because of its electrical properties and high heat capacity. The frequency range of effective water loads may cover several thousand megahertz with proper absorbing element design. Heat removal is facilitated by the use of well-known heat exchanging techniques. Water, often used as a coolant for solid loads, greatly expands the capabilities of such loads.

To avoid gross errors, it must be kept in mind that dummy loads are subject to certain limitations. There is a finite frequency range over which they will present a good impedance match to the system, so caution must be exercised to see that measurements are not attempted outside of this range. The effects on signals outside the effective range of the load should be recognized even though those signals are not being measured at the moment. For instance, although a termination may be matched at the fundamental frequency of a transmitter, it may totally reflect some of the harmonic signals and cause oscillator-frequency-pulling or result in voltage breakdown in the system. The possibilities of nonlinear behavior, particularly with high-power signals, should be recognized.

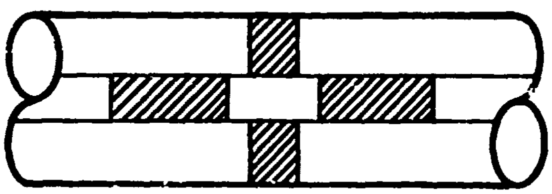
For some tests the antenna is the only practical termination, and for others it will be more a logical choice than an absorbing type of termination. Analysis of the situation by the EMC engineer should result in the appropriate selection. The antenna will probably not be an appropriate termination to the harmonic outputs of a transmitter. A very important advantage to using the antenna as a termination is that it represents the actual operating condition and will give a

more realistic picture of the electromagnetic compatibility of the system.

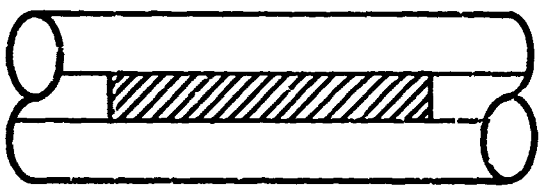
Attenuators

There are two principal reasons for using attenuators: they are often required to absorb excessive power that may damage measuring equipment, and, because they are designed to close specifications, they are useful to establish an impedance reference for insertion loss and power measurements.

An attenuator is a resistive device of which both the input and output ports present a good impedance match to the transmission system in which it is used. The construction techniques used affect the frequency characteristics. Figure 17-11 shows two basic techniques used in constructing coaxial attenuators. The "tee" attenuator is useful from DC up to 4 or 5 GHz, depending upon the reactance properties of the resistive elements. The frequency at which the resistive elements first exhibit appreciable reactance depends upon the properties of the absorbing material and the construction details of the elements. A distributed-line technique of replacing a portion of the transmission line with an absorbing element, as shown in Figure 17-11 (b), is often used to make an attenuator that shows uniform attenuation and impedance properties from about 2 to 12 GHz.



A. "TEE" ATTENUATOR



B. DISTRIBUTED LINE ATTENUATOR

FIGURE 17-11 CONSTRUCTION OF COAXIAL ATTENUATORS.

A standard technique used in waveguide attenuation is the placement of a resistance card parallel to the electric field. By using properly-shaped cards, waveguide attenuators can be constructed to cover a standard waveguide frequency range. Attenuator impedance variations with frequency must be kept in mind, and measurements should not be relied upon in the region where the impedance of the attenuator deviates extensively from that of the basic system.

A variety of attenuators could be selected to cover most of the testing requirements. To allow maximum usefulness, the frequency range should be as wide as possible. Coaxial attenuators should extend to 4.5 GHz, at least, or 10 to 12 GHz, if possible. Waveguide attenuators should cover a waveguide band as a minimum range. Models are commercially available to meet these requirements

with a moderately low impedance mismatch, (about 1.5:1). Some situations may require a closer match, in which case more expensive precision units must be sought or more narrowband versions must be used.

A 5-watt power rating, generally adequate for most problems, is a readily-achievable goal at moderate expense. There are situations, such as that discussed in connection with directional coupler selection, which require attenuators of a 15- or 20-watt power rating.

Attenuation values of 3, 6, and 10 dB should be adequate for most applications; more attenuation can be obtained by cascading several units in series. When power dissipation is a problem, the unit with the least attenuation should be inserted nearest the power source.

Switches

Audio and power switches are exempted from this discussion. The need for and uses of RF switches will be covered in the later discussion of measurement systems.

An RF switch serves the normal function of allowing a signal to be applied to two or more alternative paths. The common function of simply interrupting the path is not of concern here.

The method of switching can be either mechanical or solid state. The mechanical method involves the physical reorientation of the transmission line, whereas solid-state switching involves biasing a semiconductor to the saturated state for the "On" condition or to the reverse-biased state for "Off."

Mechanical and electrical switching are terms used to denote whether reorientation of the transmission line is done manually or with an electric motor. The mechanical method of switching is the more common method. One type of coaxial switch that uses a "pull-turn-push" operation incorporates a flexible coaxial line that mates under spring tension with the desired output jack. Another version of the coaxial switch consists of a short coaxial section that is milled into mating blocks of metal. This coaxial section joins the pole of the switch to the output terminals by precise alignment with these junctions under adequate spring pressure to insure good electrical contact with the inner and outer conductors of the line. This technique affords excellent characteristics to about 11 GHz.

Characteristics desirable in a switch for a measurements system are low insertion loss, uniformly low VSWR, low leakage, and high isolation between ports. The insertion loss should not exceed a few tenths of a dB, since a flexible system will probably include several switches, which could result in excessive power loss. This in turn would decrease the sensitivity of the system. As with all other accessory items, the impedance must be close to the rest of the system. The switch provides a physical break in the transmission line and, as a consequence, is subject to radiating energy because of an imperfect joining of conductors.

This radiated field could cause erroneous indications in the various measuring devices due to pickup by antennas, poor transmission line shielding, or case leakage. High isolation between ports is necessary to prevent signals that may be

present at ports temporarily not in use from causing interference with the signal being measured or from causing erroneous indications on the measuring device. The final design of the measuring system will determine the number of signal ports necessary on each switch and whether the electrical or manual method of switching is desirable.

Isolators

An isolator is a ferrite device whose attenuation and phase characteristics are nonreciprocal, that is, their values depend upon the direction of transmission. The attenuation in the forward direction is a few tenths of a dB and in the reverse direction, 15 to 20 or more dB.

Isolators meet a definite need when signals propagating in one direction must be attenuated while signals propagating in the reverse direction must pass freely. This is particularly true in the receiver intermodulation test in which the output of one generator is allowed to pass freely to the receiver while keeping the signal from the other generator from causing intermodulation in the first generator's output stage.

Ferrites have been shown to exhibit nonlinear properties that can cause mixer action and harmonic generation. Therefore care should be taken, especially under high-power applications, to ensure that interference is not generated in the isolator and errors are not produced in measurements. Octave band coverage is available from 250 MHz to 8 GHz and full waveguide bandwidths are available from 8.2 GHz to 40 GHz. Below 1 GHz, isolation of 20 dB is difficult to achieve over an octave range. Octave or waveguide band coverage is generally available only in low-power units. This is not a major restriction for EMC testing, since isolators find their primary usefulness in the low-power signal paths. One practical restriction to isolators may be their cost. Individual units are expensive and several may be required.

Transmission Line Adapters

It is often desirable to be able to convert from one transmission system to another, such as from waveguide to coaxial. For this purpose, transmission line adapters such as waveguide-to-coaxial adapters, are necessary. Suppose an L- or S-band radar transmitter is to be tested to determine the emission spectrum in order to investigate the possibilities of interference with a missile control complex. If the radar has waveguide outputs and the measurement system is a coaxial system, adapters are necessary to go from one system to the other.

Adequate adapters are generally available to adapt coaxial systems to waveguide as high as 22 GHz with low VSWR. Adapters are limited by certain restrictions that should be borne in mind. Their range is usually one waveguide band. Care should be taken when measuring signals whose frequency lies beyond that range where only the dominant mode can be supported in the guide. The field probes of the adapters are usually designed to sample the electric field maximum for a particular mode existing in the guide; for any other mode, the exact amount of sampling is doubtful.

Suppose the fourth harmonic output of an L-band transmitter is to be measured to determine if it meets some specification. The measurement of the power level of the fourth harmonic with a coaxial-to-L-band adapter will be questionable unless the adapter is calibrated with an exactly duplicated field configuration in the guide. Even if the field could be duplicated, the probability that this same configuration would exist for more than one measurement on the transmitter would be extremely small. The techniques involved in making multimode power measurements are rather complex.

Filters

Extraneous signals can often introduce errors into interference measurements. These errors can be in the form of spurious responses to the extraneous signals, excessive noise in the system, or overloading of measuring instruments. Filters can be extremely useful in keeping the extraneous signals from interfering with the measurements.

There are four basic types of filters: low pass, high pass, bandpass, and band reject. The particular type required depends upon the conditions of need.

Harmonics of the fundamental frequency of a signal generator can cause troubles similar to those mentioned above. A proper low-pass filter can be used to attenuate these harmonics. A characteristic of a low-pass filter is that its stop-band attenuation typically begins to deteriorate at about six times the cutoff frequency. This fact should be recognized in the application of filters. The attenuation of high-pass filters begins to increase again at about two to three times the cutoff frequency. A characteristic of all reactive filter types is that the impedance is resistive and matched only inside the bandpass. Inside the stop-band region, the filter reflects the incident power; this can be a serious limitation when using a filter to attenuate a high-power signal. For sufficiently high-power systems, conditions might result that would lead to voltage breakdown in some portion of the system. The absorptive type filter does not have this drawback.

Variable filters are more versatile than fixed filters for interference testing. Variable "tracking" filters are becoming generally available to meet the requirements of a measurement system and are specified for certain tests to MIL-STD-462. To achieve the comparable versatility of variable filters, a greater number of fixed-frequency versions would be required. As a minimum requirement, cutoff frequencies should be chosen such that the next higher cutoff is 1.8 times the preceding one. This enables differentiation between the fundamental and second harmonic. The attenuation characteristic should be steep enough to present at least 50 dB to the second harmonic for a low-pass filter, or to the fundamental for a high-pass filter.

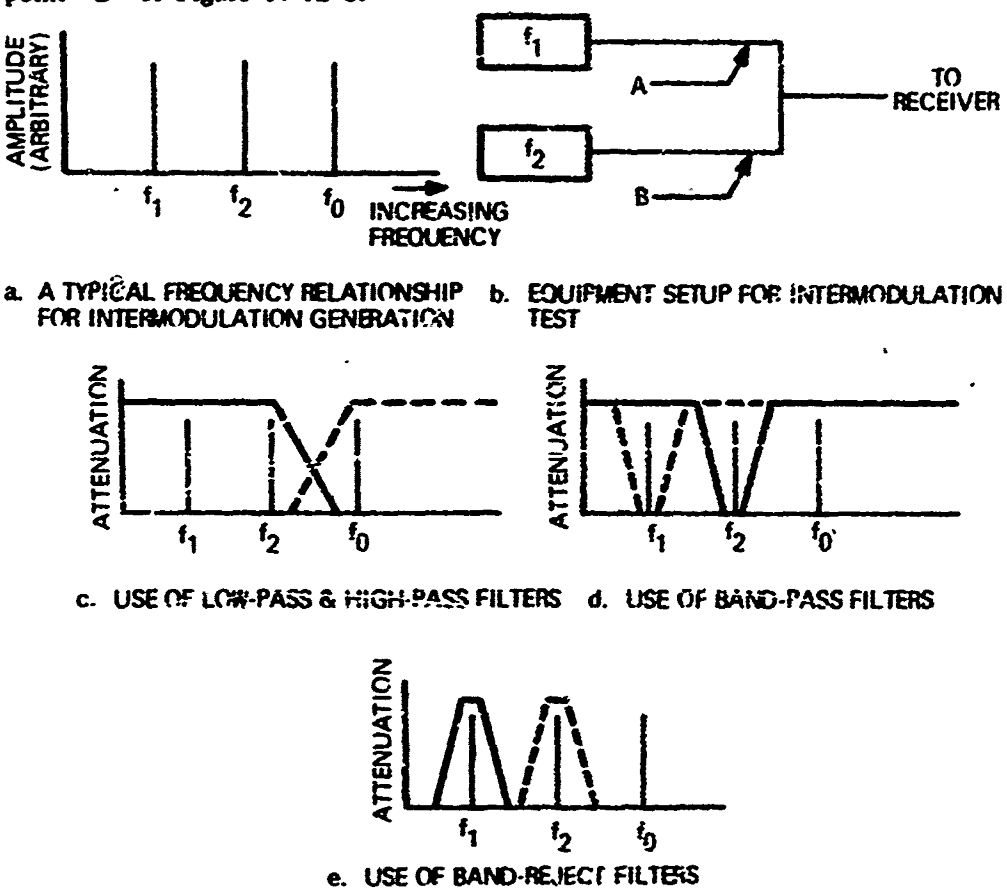
In the receiver intermodulation test, it is often difficult to distinguish the receiver intermodulation response from the products generated within the signal generators. Filters can be used to advantage to keep the signal from one generator from reaching the other without restricting its access to the receiver. Basically, the test consists of two signals applied at the receiver antenna terminals.

Intermodulation is produced by the mixing of two or more signals (such as f_1 and f_2) present in the receiver front-end. The signals are related to the tuned frequency (f_0) by

$$\pm mf_1 \pm nf_2 = f_0 \tag{17-4}$$

Where m and n are integers.

Figure 17-12a shows a possible frequency relationship between f_1, f_2, and f_0. The simplified diagram of part b indicates the way in which the two interfering signals are applied to the receiver. Figures 17-12 c, d, and e indicate how the various filter types can be used to keep the output of one generator from reaching the other. The filter characterized by the dotted curve would be inserted at point "A" and the unit described by the solid curve would be positioned at point "B" of Figure 17-12 b.



a. A TYPICAL FREQUENCY RELATIONSHIP FOR INTERMODULATION GENERATION

b. EQUIPMENT SETUP FOR INTERMODULATION TEST

c. USE OF LOW-PASS & HIGH-PASS FILTERS

d. USE OF BAND-PASS FILTERS

e. USE OF BAND-REJECT FILTERS

FIGURE 17-12. THE USE OF VARIOUS FILTER TYPES TO MINIMIZE GENERATOR INTERMODULATION

INTERFERENCE MEASUREMENT SYSTEMS

Previous sections have been devoted to various aspects of interference testing such as measurement techniques, test equipment, and test environments. The following discussion will present a possible approach toward streamlining the performance of the many tests called for by MIL-STD-461A. It should be recognized, however, that not all testing conditions are suited to efficient use of an integrated system. But even for those situations where a unified system would be of no particular advantage, nothing prevents an individual test setup from being used as required.

To perform all tests required by various specifications, certain items of measuring equipment are required or are highly useful. Signal generators, interference measuring sets, frequency measuring systems, and other interference measurement components are essential. A spectrum analyzer is highly useful for a visual display of signal spectra, and it is necessary for certain analyses of pulsed systems as well as to determine the frequency modulations of a signal by the use of the "zero count" method. The measurement or observation of the modulation characteristics of a signal is greatly enhanced by the use of a modulation meter, but the state of the art is limited in this field. AM instruments are generally adequate to meet requirements for which their use is indicated, but frequency deviation measurement capabilities are limited above 1 GHz. A power meter is often required to determine the average power output of a system, and a standard response indicator is a useful instrument when the response of a receiver must be monitored by personnel who are at a considerable distance from the receiver.

Generally, the performance of accurate and meaningful EMI tests is a time-consuming operation, which means it is also a costly one. The avoidance of having to set up and take down equipment for each of the ten or so separate tests called for in specifications is an economical move. In the gigahertz range, frequent making and breaking of connections results in a greater probability that a poor connection will result, causing excessive VSWR and insertion loss that produce errors in test data.

Human fallibility enters into test setup. The omission or inclusion of a component at an inappropriate time or place can result in worthless data. If the data are not analyzed by a person thoroughly familiar with the equipment under test, the over-all system, interference testing procedures, and expected results, a thoroughly inaccurate description of the interference characteristics of the equipment can become permanently recorded.

In EMC testing, large quantities of data must often be taken to adequately describe the compatibility of a piece of equipment or a system with its environment. Manual acquisition of this data is a slow process even with an integrated measurement setup. The system designer should use as extensively as possible devices that operate automatically or semiautomatically. Interference-measuring sets are available to cover from 1 to 10 GHz with built-in automatic tuning capabilities. With appropriately coupled recording facilities, the output spectrum of a transmitter can be scanned and recorded rapidly. Signal generators with automatic

sweep capabilities, such as provided by backward-wave oscillators, should be used extensively. These devices can sweep an octave range in as short a period as 0.01 second. Swept frequency capability would be useful in receiver front-end rejection tests in which the receiver must be tested over a wide range. Automatic signal tuning capability could be used in conjunction with the standard response indicator principle referred to earlier to perform the receiver tests quickly as well as automatically.

Other automatic measuring systems such as automatic wideband spectrum display systems can be effectively used in EMC programs. The automatic measuring system can be no more accurate than the accessory items necessary to get from the test point to the measuring instrument. The present state of the art on many items prevents fully effective use of extremely broadband systems. Adequate performance of signal samplers is generally not available over more than an octave range. Some directional couplers will work over a wide range but only at the expense of degraded performance. Attenuators may be difficult to obtain that exhibit the necessary impedance match and constant insertion loss required in the system. If the item of equipment being tested uses a waveguide transmission system, coaxial-to-waveguide adapters are usable only over the frequency range of the waveguide band. These considerations indicate that there are definite limitations on the full use of automatic measuring facilities.

Few guidelines are defined in the specifications for the selection of measurement frequencies. A great deal of time can be wasted in taking data which is not needed. By means of a thorough analysis of the receiver, transmitter, or complex, the EMC engineer can select points that indicate the greatest possibility of interference.

If the receiver front-end rejection test is performed first, the data can be used as a guide for choosing other measurement frequencies. Suppose the rejection characteristics behave as in Figure 17-13. The tuned frequency is represented as f_0 and spurious pass bands are indicated by f_1, f_2, and f_3. The receiver would tend to experience spurious responses near these regions of low rejection as well as in the region where the rejection is permanently degraded, above f_4. Two signals in the region above f_4, with the proper frequency relationship, can result in intermodulation in the receiver. If the operating environment is known or can be predicted, the receiver should be tested at those frequencies where particularly

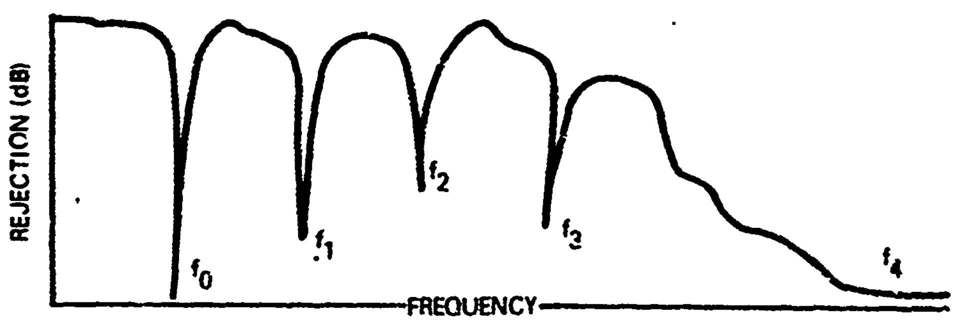


FIGURE 17-13. POSSIBLE RECEIVER FRONT-END REJECTION CHARACTERISTICS

strong signals exist. If moderate or weak signals are expected to exist near a "hole" in the rejection characteristic, i.e., f_1, f_2, f_3, or above f_4, a test should be conducted at these frequencies.

The nonsignal-line conducted susceptibility test should emphasize those frequencies where the strongest signals can be expected. These frequencies can best be determined by examining the transmitters expected to be nearby. If a transmitter-receiver complex is being measured, an analysis of the transmitter schematic diagram will reveal most of the possible signals. If units near the receiver are known, the same analysis can be applied to their circuit diagrams. If no information is available on the possible signal sources that near the receiver, the next best approach is to perform measurements at frequencies that will give fair coverage over the normal operating range.*

Analysis of the transmitter circuit diagram is the best starting point in selecting the most logical frequencies of signals that could produce interference. The transmitter AFC local oscillator is a likely source of signals. Depending upon the manner of achieving the local oscillator signal, the AFC system can be a rich source of many extraneous signals. Any other signal sources such as special function generators should also be examined. The transmitter should be examined at three frequencies (low, medium, and high) or more in its tuning band. It should also be tested while operating in its normal output mode.

For a communications or radar complex, the above comments also apply. Much time and money can be saved by first analyzing the system to establish the most likely sources of interference. Other equipments, such as motors, should not be overlooked as possible sources of interference.

Measurements of radiated emission and susceptibility can also require an inordinate amount of time. Tests should be made at those frequencies where the transmitter is most likely to exhibit emissions or where the receiver will most likely show a response. Another factor that enters into radiated EMI measurements is the location of the test antenna.

Performing measurements in the near field of an antenna is a complex problem that will not be dealt with here other than to say that the sampling antenna should be oriented near points where signals can be expected to be transmitted through the equipment case. Ventilation holes, meter faces, and seams are examples of paths through the case where the shielding might be inadequate. Signal ports such as the antenna connection, unused IF input/output jacks, modulator input, and headphone jack should also be checked for leakage.

This chapter has covered certain techniques of EMI measurement. The EMC engineer is confronted with accuracy requirements on one hand and with equipment capabilities on the other. Where these two situations are incompatible, a compromise must be made. Several items of accessory equipment necessary to perform EMC testing were briefly discussed, with emphasis given to sources of errors in test operations.

*For typical frequencies see MIL-STD-449C, *Measurement of Radio Frequency Spectrum Characteristics*

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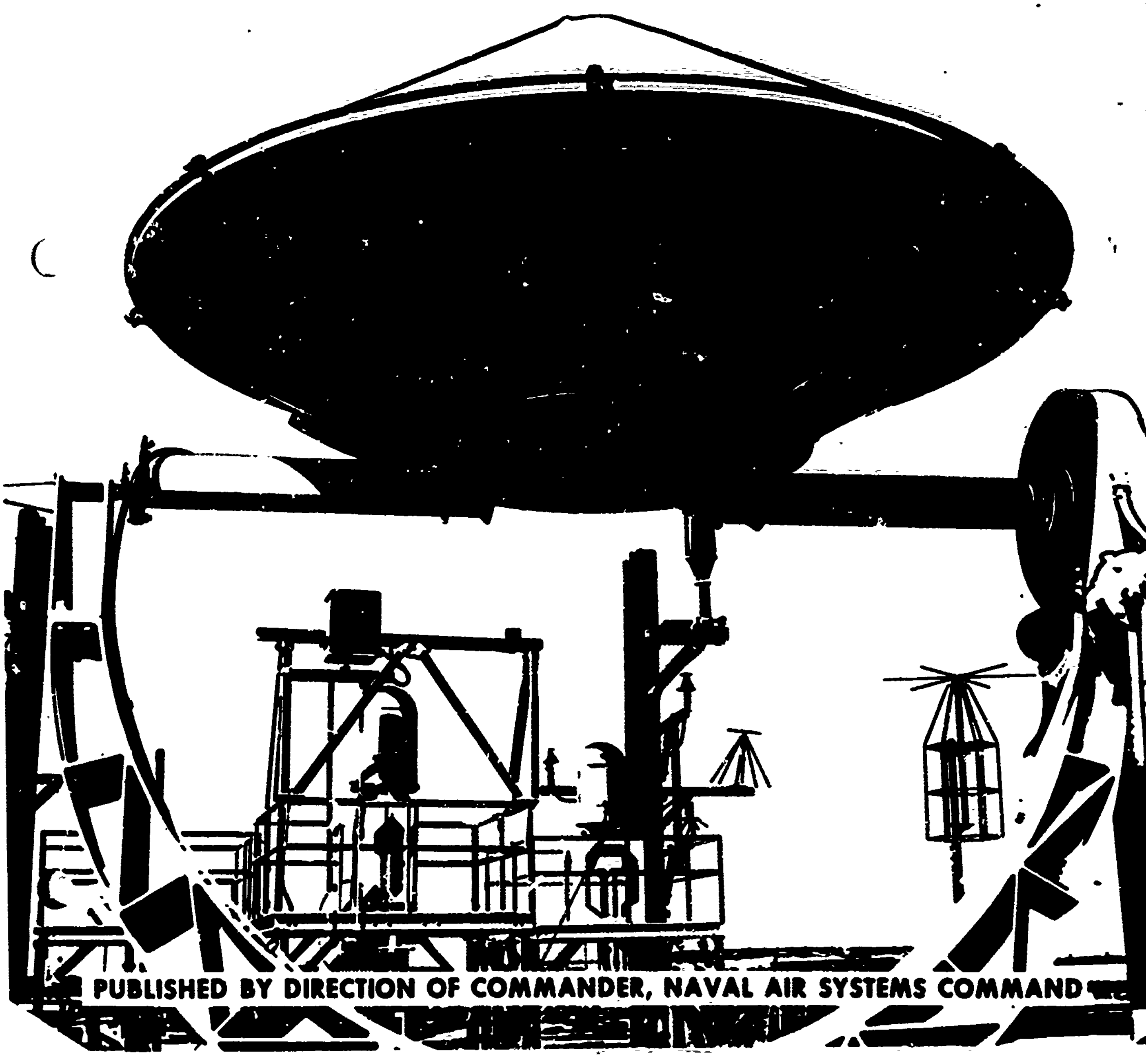
NAVAIR 5335

NAVAL AIR SYSTEMS COMMAND

ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 18



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CHAPTER 18
ATMOSPHERIC INTERFERENCE AND LIGHTNING PROTECTION

CONTENTS

ILLUSTRATIONS

INTRODUCTION

The natural interference environment consists of noise from many sources including the atmosphere, the sun, the galactic plane, and the cosmos. The relative contribution of these sources to the total interference varies considerably with frequency, time, location, direction, and other parameters. Certain aspects of atmospheric interference are of particular interest to the designers and operators of airborne communications-electronics systems because of the impact on systems performance and safety. The deleterious effects of precipitation static and frictional charging are well known. Thunderstorms and lightning have even more serious effects on the performance of equipment and on safety of flight. This chapter will discuss the causes and effects of these phenomena and the recommended design considerations for their control.

The control of precipitation static and consideration of lightning effects on aircraft systems goes beyond the design of C-E equipment into that of the airframe. In discussing these phenomena, emphasis is on personnel hazards and equipment damage. While this is outside the realm of radio frequency interference, it is customary to include precipitation static control and lightning control in the EMC package.

Since aircraft must be flown in adverse weather, electronic equipment on board must continue to function without significant degradation of performance while the vehicle is subjected to high and rapidly varying charge potentials. There is also to be considered the effect on ground support equipment of atmospheric interference. People in an airborne vehicle still require communication with shore or ship-based equipment, which must also be designed to restrict the effects of natural atmospheric potentials and resulting interference. Adjacent lightning strokes, as well as remote lightning strokes, will affect the operation of electronic equipment or even damage it.

DEFINITION

Electromagnetic interference of atmospheric origin is nonsinusoidal broadband electrical energy propagated in space or generated locally and conducted through antenna or power lines to receiving equipments. It is either impulsive, resulting from instantaneous electrical discharges, or random in frequency, arising from electrical discharge in ionized pockets of corona or streamers. Such atmospheric energy causes high noise levels, undesired response, malfunction, or degradation of performance of electronic or electrical equipment and covers the entire electromagnetic frequency spectrum in varying degrees of intensity. For convenience, in this discussion it is divided into cross-field, precipitation static, and thunderstorms.

PRECIPITATION STATIC (P-STATIC)

Locally-produced atmospheric interference is generated by electrostatic charges leaking off the surface of aircraft due to cross-field induction or during passage through rain, ice crystal clouds, or wet snow in turbulent and ionized clouds. These effects are classified as cross-field and precipitation static (p-static).

CHARACTERISTICS AND CAUSES

P-static is broadband energy received as continuous impulses similar to shot noise. Its effect at a receiving antenna is usually weighted in frequency, deviating from Gaussian distribution, and the weighting sometimes shifts at an audio rate. In speech communication equipment, it produces a rushing sound that blankets most input channels. When shifting frequency weighting occurs, FM receivers, unable to cancel the unsymmetrical interference, detect both rushing and screaming sounds. The received intensities are high, being generated in the immediate vicinity of the airframe and thus being tightly coupled to the antenna system.

The principal source of p-static is the passage of aircraft through uncharged particles, which generally deposit negative charge on the vehicle through triboelectrification charge separation, not through electrical contact with the electrostatically charged particles. Nature has provided both the energy and the mechanism for generating the charge. The aircraft charge accumulates on the relatively small aircraft capacitance of roughly 700 to 1000 pF, depending upon aircraft size.

Energy for atmospheric charging is supplied in the form of warm, moist air rising rapidly to high altitudes. Expansion and resultant cooling gives rise to precipitation, which in turn liberates heat to accelerate the rising air current. The mechanism for electrostatic charge generation is supplied by the friction of air with the raindrops where the relative velocity, exceeding twenty-six feet per second, tears off small droplets. Physical separation of these small droplets has been shown to leave the droplets with an excess of electrons. The rising rain mist, therefore, gives the lower part of the cloud a negative charge, while the raindrops falling to earth are positively charged. When an air vehicle moves through such charged areas, its motion through the electrical field induces charges of opposite polarities on extremities of the aircraft. This is due to cross-field induction, the basic physics principle of electrostatic induction in a conducting body when it is immersed in a static field. Polarities may reverse as the aircraft flies between clouds having different polarities with respect to each other. See Figure 18-1.

The rate of charge depends upon air speed and particle contact density rate. Particle density generally leads to linear charging, increasing the rate of charge in direct proportion to the increase in weight of material striking a unit area of the surface per unit time.

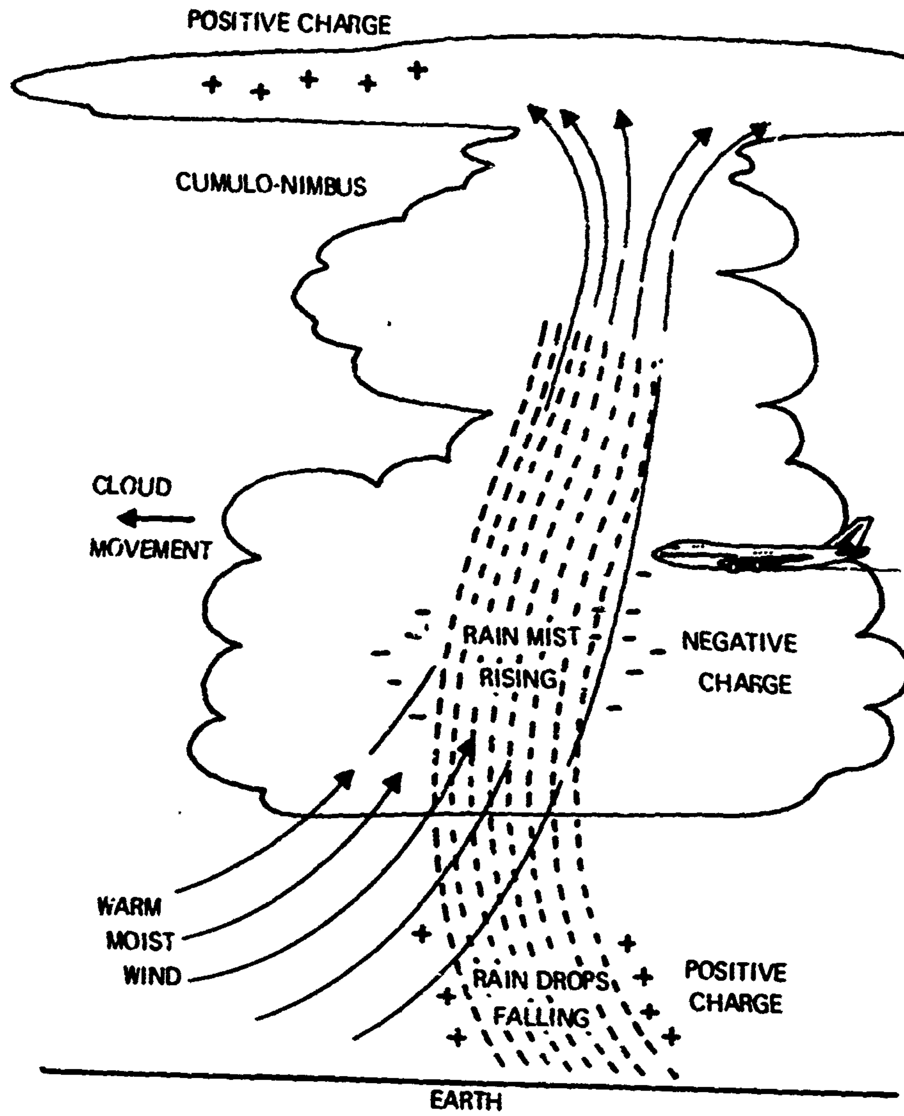


FIGURE 18-1 CHARGE GENERATION IN A CLOUD

This charge, establishing a relative potential up to 100,000 volts, behaves according to the principles of static electricity, concentrating at extremities and sharp points. Measurements made on aircraft in flight show that static electricity may cause electrostatic flux densities at wing tips up to twenty times those existing in the mid region of the fuselage (Figure 18-2). Current flow in all-aluminum low-resistance skin of the aircraft is almost nonexistant, except where currents of not more than a few milliamperes follow quick polarity reversals.

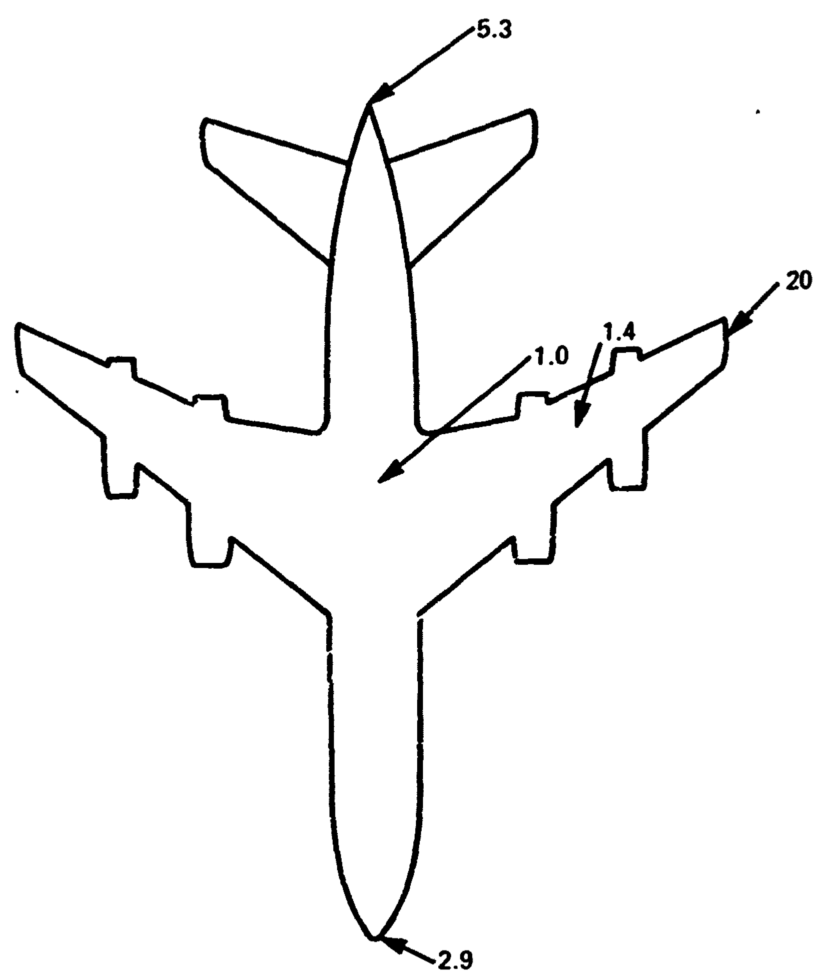


FIGURE 18-2 RELATIVE ELECTROSTATIC FIELD CONCENTRATION POINTS ON AIRCRAFT

Such electrostatic charges accumulate until the air breakdown potential is reached. While the breakdown potential gradient at sea level may be 30,000 volts per centimeter, this may be reduced to lower values at higher altitudes. Both air density and the surface density of charge are parameters that influence the breakdown potential gradient. Air density becomes less as altitude above sea level increases. It also becomes less at high-life areas, such as along the upper surface of wings and at propeller blades. Surface density of charge depends upon geometry. Experiments with charged balls have shown that the surface density of charge increases as the radius of a ball is reduced. For instance, if one large and one small metal ball are connected together at opposite ends of a metal rod insulated from ground, and an electrostatic charge is supplied, the small ball will have a higher surface density of charge. The principle can be expressed as follows:

$$S = \frac{V}{4\pi r} \qquad (18\text{-}1)$$

Where:

S = surface density of charge
V = static voltage
r = radius of curvature of the surface or point

Once breakdown has occurred, a discharge will follow. Impulse discharges and multiple varying frequencies, rich in both AM and FM components and harmonics, are generated in the 0.1 to 400 MHz range and occasionally beyond. Received intensities to 100 uV/kHz are common due to the conduction of interference from the source to receivers via antennas, power lines, or other electric circuits in the aircraft.

EFFECTS ON SYSTEM PERFORMANCE

Effects that can result from precipitation static include possible failure of mission, mission abort, or, in congested traffic or bad weather, operation and safety of flight. Special consideration is required for communication and navigation equipment in the low-frequency (LF) and medium-frequency (MF) bands because of their particular susceptibility to p-static interference. For manned aircraft, the problem is especially severe because this type of interference occurs during times of low visibility, when the pilot must fly by instruments, using voice communication and radio navigation aids. In missiles and unmanned vehicles, another problem arises because digital equipments in the control system have limited ability to distinguish between noise and the desired signals.

METHODS FOR REDUCING INTERFERENCE

A number of methods and techniques are effective in reducing the static charge build-up on an airframe. These are discussed in the paragraphs that follow.

One method of reducing p-static is to avoid points, corners, and edges, in aircraft configuration, and in maintaining smooth contours in critical areas where aerodynamics permit. It is advisable to establish minimum radii for all curved surfaces, to help keep the potential of the whole aircraft uniform. This will allow the aircraft to take on a moderate charge, up to the potential at which the built-in static dischargers take effect. Propeller and rotor tips present another source of corona because of lowered air pressure and sharp contours. Good grounding techniques and smooth, clean surfaces are recommended to prevent buildup of local static charges. Corona at long-wire transmitting antennas is reduced by increasing the wire diameter to raise the corona point; and by insulating the wire with a thick plastic sheath.

A second control to minimize pickup and conduction of p-static is to shield and ground all cables to navigational lights, electric motors, electric heaters, and all sensor leads such as those from fluid-level and temperature detectors. Corona-generated interference can enter at any point where the skin of the airframe is pierced; it is here that grounding and shielding must begin. This will also prevent surge penetration into the electrical systems from lightning strikes to the aircraft.

A third control of p-static is to use static dischargers. The first widely used type was a passive unit composed of cotton fibers impregnated with carbon and enclosed in a plastic sheath. One and one-half inches of fibers were exposed at the free tip, providing many fine points through which corona could discharge. The bundle was clamped in a bracket and attached to the trailing edge and extremities of wings, elevators, and rudder. The carbon impregnation distributed resistance for suppression of RF interference.

For use at higher air speeds, more rugged passive static dischargers have been developed. The most successful type uses a solid but resilient plastic body impregnated or coated with a slightly conductive material. At the tip, a pair of tungsten needle points permits a low-voltage corona discharge. The plastic body locks into its mounting retainer but is replaceable, since both the plastic and the needle points suffer from weather erosion and have a life expectancy of about five hundred hours. Another type, for wing tip mounting, is a rigid blade of fiberglass or nylon wherein a conductive coating on the plastic bridges the gap between the tungsten needle points pressed through fiberglass and the metal clamp-in base. MIL-D-9129B describes the approved military types.

Continuing research is being directed toward more flexible plastic p-static dischargers for use at supersonic speeds. The requirement is severe for speeds up to Mach 3. More rugged types are under study to reduce lightning damage. Solid-state nonlinear resistance elements are being considered as a means of lowering the resulting noise levels during corona discharge.

Active dischargers are being developed to further reduce p-static interference. These are in the form of a wing-mounted high-voltage power supply automatically controlled by an electrostatic sensor. Under conditions of p-static, such power supplies counteract the charges, keeping the aircraft essentially neutral. This technique has been used successfully on helicopters, where the high tip-speed of the rotor blades creates problems similar to those associated with propeller driven aircraft.

Helicopters are subject to another static charge problem. The dust clouds that the helicopter down-flow generates during stationary flight for unloading cause severe friction charging of the vehicle. This creates serious hazards to the personnel loading fuels and ordnance, thus requiring the use of active dischargers even though active dischargers themselves present some problems.

A fourth technique in p-static control is the use of a shielded-loop antenna or, for high speed jets, flush-mount antennas. Either type of antenna is relatively immune to electrostatic interference emanating from corona discharge at various places on the aircraft. Coaxial cables used with these antennas should be grounded to the skin of the aircraft at the point of entry.

FRICTIONAL CHARGING

Frictional charging is defined as a local occurrence resulting from friction (triboelectric effect) between aircraft and particles in the air, or between aircraft and nonconductive liquids such as fuel flowing into the tanks of the aircraft. Friction separates charges from impinging particles and generates an electrostatic charge on the aircraft in what can be considered dry-weather phenomenon. Even in a relatively clear atmosphere charging may occur from contact with dust, salt, or snow, or from the presence of the vehicle in thunderstorm crossfields.

CAUSES AND EFFECTS

The interference generated by frictional charging is in two forms: first is the noise as each particle contacts the antenna, and the second results from the charge leaking off as corona. Frictional charging can take place on the ground, as in a dust storm, or in the air under a variety of conditions. The particles involved include snow, ice crystals, sand, dust, smoke, and exhaust system particles from lead aircraft in tight formation flying.

The type of particle present controls the resulting polarity of charge, to some extent. Dry snow impinging upon aircraft almost always produces a negative charge. This has been demonstrated in the laboratory as well as in flight. Air temperature controls the rate of charge, with the rate becoming maximum at about -10°C. These conditions prevail in any weather at intermediate altitudes to produce severe interference. Fine ice crystals encountered at high latitudes or the form described as ice spicules composing cirrus clouds, occurring generally above 30,000 feet, produce equally severe interference at all seasons.

Sand, dust, smoke, and exhaust particles generate charges, but the polarity depends upon aircraft finish, air temperatures, and atmospheric charge centers. The most commonly used aircraft paints and waxes lead to a negative charge on the aircraft at air temperatures between -5° and -15°C. On the other hand, a finish using titanium dioxide (TiO_2) or a pigment of colloidal silica in cellulose nitrate generates a positive charge on the aircraft at air temperatures between 0° and -10°C. The polarities cannot be reliably predicted at temperatures higher or lower than those indicated. Experience has shown that clean bare aluminum is the most neutral material over the widest temperature range for all types of particles encountered. Even nonconductive surfaces such as radomes develop a local charge accompanied by a type of discharge known as streamering unless they are protected with a thin, somewhat conductive coating that is properly grounded to the aircraft metal structure.

Helicopters, while hovering in snow, sand, or dust, may experience frictional charging. Potentials from -200,000 to +60,000 volts have been recorded on different occasions, depending upon the type of aircraft, the windborne particle material, and the atmospheric field gradients, which can reach 5,000 volts per meter or more under incipient lightning conditions. To neutralize these potentials, active static dischargers have been installed in helicopters in the form of high voltage power supplies capable of delivering at least 100 microamperes at either polarity as the occasion demands.

THUNDERSTORMS

Thunderstorms, being gigantic lightning generators, create an impulsive form of broadband electromagnetic interference. A continuous background of short pulses that are completely random in recurrence, phase, and amplitude, is received, from the lowest usable radio frequencies to the VHF band and occasionally beyond. This is the result of hundreds of thunderstorms scattered over the earth, and the interference cannot be avoided but its effects can be reduced to some degree.

One type of interference produced by lightning is the whistler, so called because of its characteristic drawn-out descending pitch. The whistler is a naturally occurring transient disturbance lasting about one second and appearing predominantly in the VLF range. It is an effect caused when a lightning discharge travels along lines of magnetic force of the earth's field and is reflected back to the origin from a magnetically conjugate point on the earth's surface. Related to whistlers is another class of natural transient phenomena known as VLF emissions, including dawn chorus, hiss, and quasi-constant tones. This type of interference is most prevalent in the auroral zones and is usually associated with a disturbance of the earth's magnetic field.

One more disruptive and destructive aspect of the above interference occurs when operating in the vicinity of an active thunderstorm. Prevention of lightning damage and electrostatic hazards to the aircraft should be the first consideration

in planning and designing airborne electrical and electronic equipment. A review of the known principles of lightning generation and its effects is presented as an aid in understanding preventive measures.

LIGHTNING DISCHARGES

For over two hundred years, since the inspired experiments of Benjamin Franklin, it has been known that precipitation within rain clouds, where strong updrafts of warm air prevail, generates electrostatic charges. It was believed that some form of friction between air and falling water drops, possibly motivated by the condensation of water vapor at the molecular level, was responsible for displacement of electrons. On such a grand scale where the clouds are miles high, it was understandable that even slight frictional charging could accumulate significant electrostatic charges.

Such a thundercloud, cumulonimbus, accumulates a negative charge at its base and a positive charge at the ground below as well as at its top. Dependent upon the velocity of the rising current of air in its center, the charge builds up until the electric field gradient is on the order of 4,000 volts/cm. between opposite poles or between the cloud bottom and the earth. This gives rise to an electrical breakdown of the moisture-laden air like the first blue flicker of a fluorescent light.

This breakdown, or movement of electrons, occurs in steps of roughly 150 feet in length, each within a period of approximately 100 microseconds. Existing gas ions are concentrated along this path, and more are created by the acceleration of electrons, forming faintly luminous low-resistance ionized ducts. An increase in field intensity at its extremities results from bridging more widely separated charged fields. In this manner, the halting advance of electron discharge known as a step leader, is usually branched and continues progressively toward regions of opposite charge.

As the step leader advances toward the earth, a corresponding but opposite ionized and luminous effect with a positive charge may be induced, appearing in a brush-like corona discharge known as St. Elmo's fire. Such an ionized zone may flash upward as a streamer from treetop or roof peak, shortening the path to the advancing step leader. When the circuit is completed, the low resistance ionized duct permits the excess electrons to drain off to the earth with an almost instantaneous surge of current with a peak amplitude on the order of, and sometimes greatly exceeding, 100,000 amperes. This all takes place in about one millisecond.

Once the main ionized channel to ground has been completed, repetitive strokes usually follow the same low-resistance path at intervals of about 1/30 second. It is believed that successive strokes discharge other charge centers, each more remote within the cloud, until the areas of high field intensities have been neutralized. Then the ionized air in the duct is dissipated by the wind and by recombination. The odor of ozone, an unstable form of oxygen, is often perceptible shortly after nearby strokes of lightning in a thunderstorm.

Persons in aircraft flying in the vicinity of thunderclouds may observe St. Elmo's fire at wing tips, projecting parts, and windshields as a warning of high field intensities and proximity to advancing step leaders. If the aircraft intercepts a step leader, the heavy current of the main electric discharge may follow the low resistance of the aircraft metal structure as shown in Figure 18-3. Burned spots and punctures of the sheet-metal skin may result. As the aircraft flies through this channel, the lightning, bending with local air flow, appears to be swept aft along the surface of the aircraft, the arc voltage drop causing breakdown and reattachment at new points along the aircraft. The evidence is a series of small burned spots separated by quite regular spaces. Multiple strokes usually follow the same ionized channel in the air mass. Where a tail extremity or other protrusion is involved in sustained or repetitive lightning strokes, there may be a main "attachment point" where the lightning flash hangs on and does considerable heating, resulting in holes an inch or two in diameter, while the previous points of contact for the same flash are separated and usually suffer little damage (Figure 18-4).

A bolt of lightning originates from a cloud formation with its base 500 to 5000 feet above the ground, and an airborne vehicle bridges only a small gap in the progress of a step leader. Because one bolt of lightning may represent an EMF of a hundred million volts, a capacitive discharge of over 200,000 amperes, and a total charge of 500 coulombs, an airborne vehicle having a potential of only a hundred thousand volts, a maximum charging rate of a few milliamperes, and a maximum charge of perhaps 5 coulombs is insignificant.

The friction charging potentials on the aircraft are not significant in relation to triggering natural lightning discharges. Aircraft do trigger natural lightning strokes by their sudden appearance into the field. This has been confirmed in simulated programs as illustrated in the Lightning Transient Research Institute mechanism of triggering lightning discharges by firing small rockets equipped with a few hundred feet of stainless steel wire as a tail.

To explain the mechanism by which broadband impulse type electromagnetic interference is generated by lightning, the data must be used to formulate a model. High-speed photography of lightning shows that the halting progress of the step leader takes place over a period of nearly one millisecond, until the gap is bridged between charge centers. Then, within about 30 microseconds, the flow of the electron stream is fully established, as shown by the brilliant light emitted from the main channel of the discharge. Surges are presumed to reach as high as 500,000 amperes, while the average is about one tenth of that. The measurements, moreover, indicate a rise rate as steep as 200,000 amperes per microsecond, with an average of 10,000 amperes per microsecond.

From these data, a trapezoidal wave having a duration between 10 and 100 microseconds and a rise time between 2 and 5 microseconds could be postulated. Published curves for interference calculations indicate that such a wave shape would have a radiation peak just below 10 kHz, and significant harmonics on a descending slope somewhere between 20 and 40 dB per decade extending to at least 30 MHz.

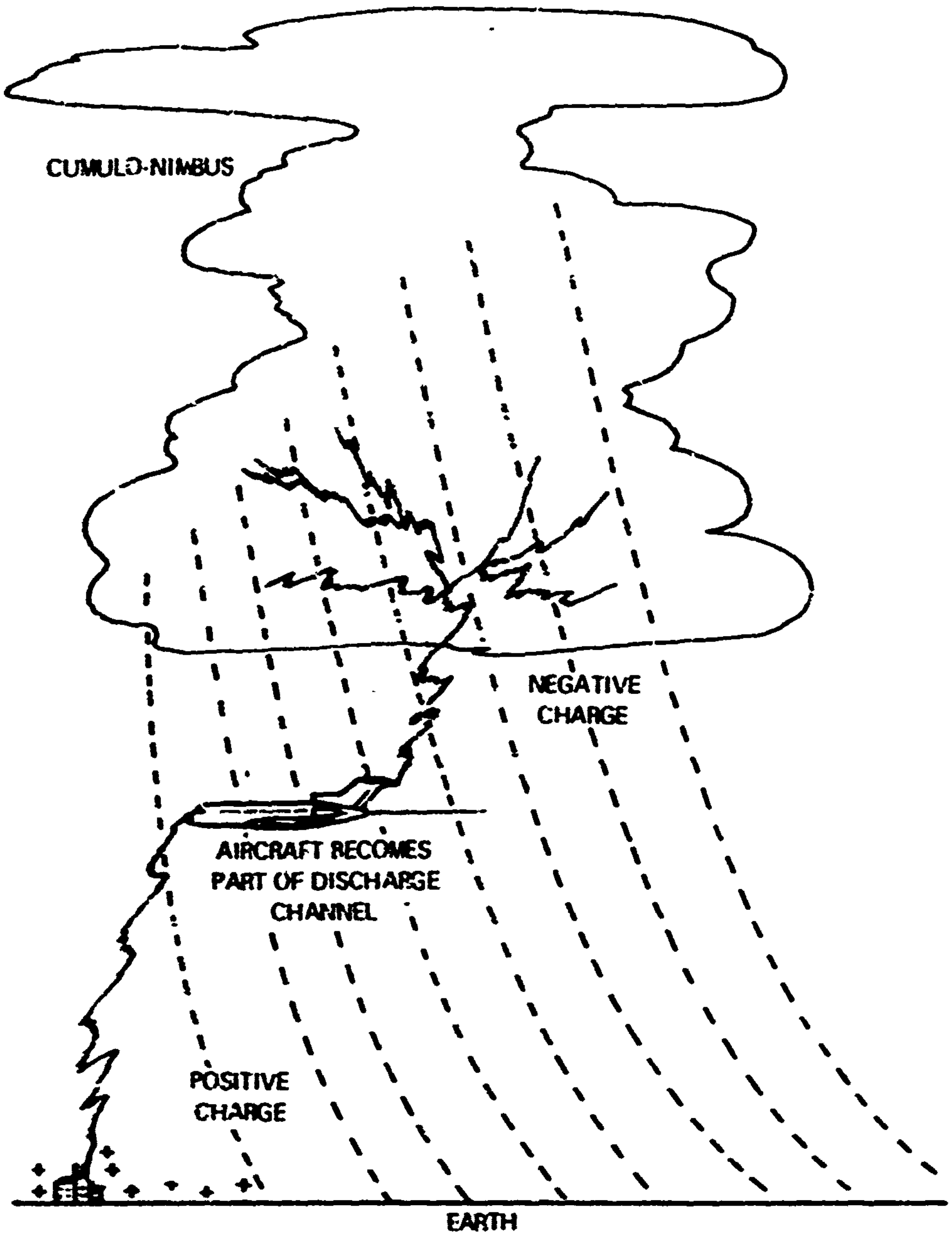


FIGURE 18-3 LIGHTNING STRIKE ON AIRCRAFT

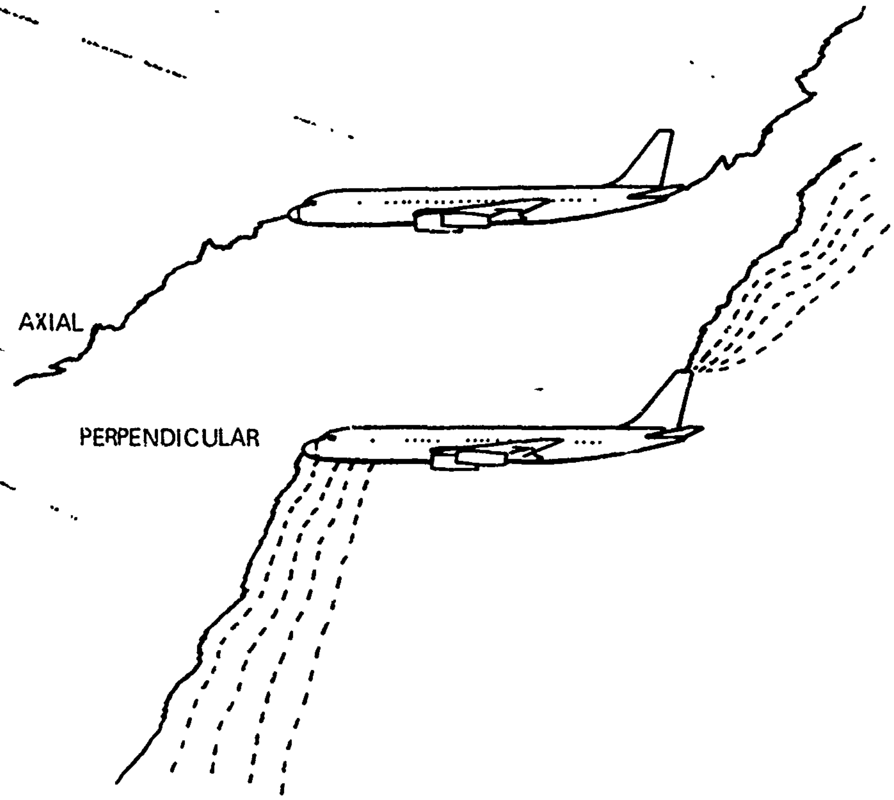


FIGURE 18-4 SWEPT LIGHTNING STROKES

EFFECTS OF LIGHTNING IN THE VICINITY OF AIRCRAFT

Lightning-caused interference can be categorized as low-level interference, high-level interference, and damaging levels of interference. Control of each requires different techniques, preferably considered during both equipment design and installation of C-E equipments.

Low-Level Lightning Interference

Low-level interference, simply known as static, is controlled primarily by use of directional antennas, shielded-loop antennas, blanking and clipping techniques applied to the receiver, and high transmitted power. In supersonic airborne vehicles, the use of flushmount semi-directional receiving antennas is a requirement. In slower aircraft, the traditional shielded loop has useful directionality and is insensitive to the electric field component of corona-generated RF. It also embodies physical contours large enough in radius to discourage corona.

Some interference can be reduced in the receiver. Foremost is amplitude limiting in wideband stages, followed by bandpass limiting in selective IF stages, up to the point of ringing or shock excitation under the impact of impulsive noise. The trade-off is between noise amplitude reduction, which varies as the square root of receiver bandwidth, and pulse lengthening from ringing, which is inversely proportional to the bandwidth of each stage. Modulation techniques that concentrate the essential information to be transmitted into a minimum bandwidth can capitalize on this principle.

High-Level Lightning Interference

More severe problems result from high-level interference emanating from lightning discharges close to an airborne vehicle. Very broadband, this interference cannot be prevented from saturating receiving equipment. The resulting voltage levels, however, can be controlled by limiters, and electronic circuits can be selected to provide high tolerance to overload as well as short recovery time. Noise AGC circuits and noise limiting circuits covering a wide range of response times and slope characteristics are available to the circuit designer. Each application is unique, requiring a trade-off between signal distortion and recovery time following saturation. Where maximum reliability is required, special techniques such as programmed gating, redundancy, alternate modes of modulation, and computer-aided data processing may be incorporated into a system.

Near-miss lightning can often induce transient energy into the aircraft electrical circuits and cause wire-bundle fires, freak acuation of relays, disrupted data channels. If equipment grounding and airframe bonding are inadequate, severe shocks may be experienced by personnel. In darkness, the lightning flash can produce temporary blindness and loss of night vision for pilot and copilot, endangering the entire aircraft unless precautions are taken. The pilot will often lower his seat level so that as little of the windshield area as possible falls within his field of vision, thereby protecting his eyes from the lightning flash.

Lightning Damage

Damage to aircraft by a direct stroke of lightning ranges from relatively minor dents and pits in the aluminum skin to extensive internal damage jeopardizing its airworthiness. When an airborne vehicle is involved in a main ionized channel of lightning, the resulting current in it has been measured and found to be as high as 200,000 amperes. This is considered as a working upper limit.

Lightning has sometimes been divided into cold and hot lightning. In cold lightning, high voltage and high current discharges of very short duration cause an explosive effect by heating air and moisture within wood and porous materials. In hot lightning, a lower power discharge continues for a longer duration, producing more widespread damage largely through ignition of combustible materials.

A summary of data from 18 commercial air carriers reporting on 740

lightning strikes indicates that 13 percent created negligible damage, 48 percent created damage requiring minor repairs, and 39 percent resulted in major damage that affected airworthiness or impaired the function of electronic equipment. Because thunderstorms cannot be avoided during tactical deployment, lightning protection must be included in system requirements. Statistics indicate a probability of one stroke per aircraft for 2500 to 5000 flight hours.

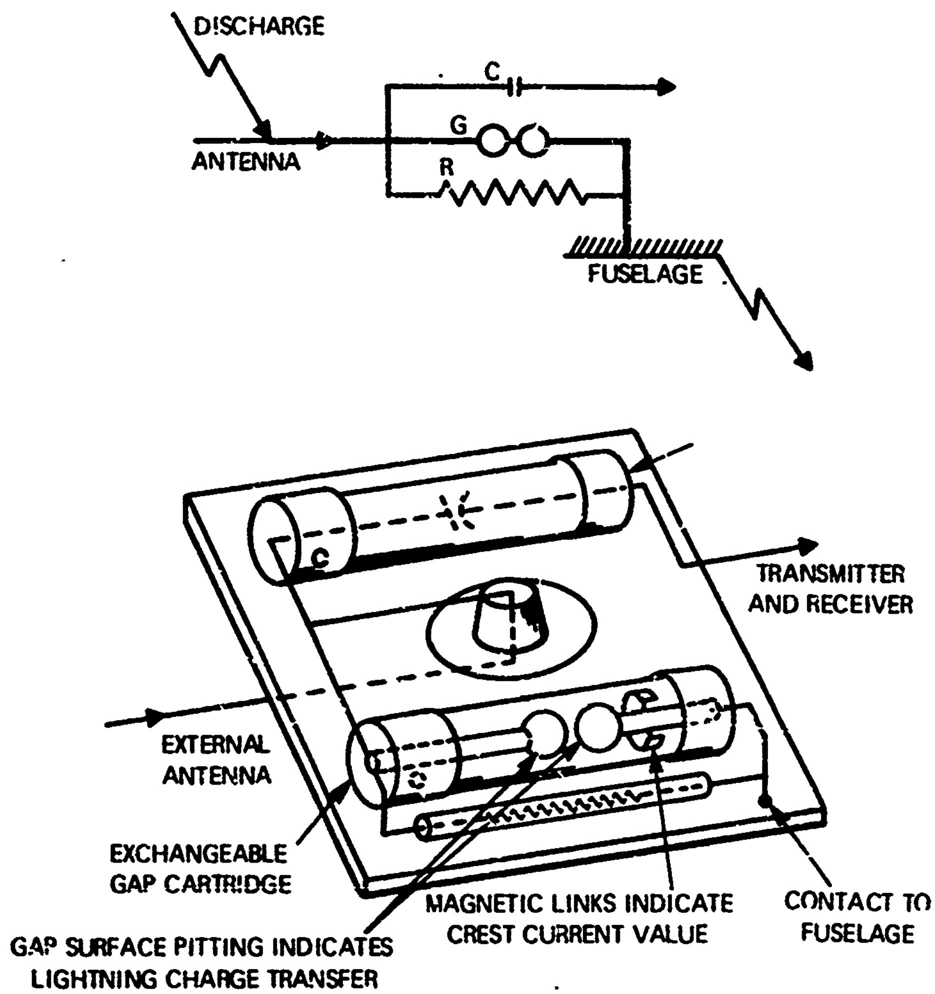


FIGURE 18-5 EARLY LIGHTNING ARRESTOR

Antenna-coupled receivers and transmitters can be protected from lightning discharges with lightning arrestors. Most of the arrestors used today are based on an early design that was originally developed as part of a flight research program. Figure 18-5 shows the layout of the arrestor and a schematic diagram of the circuit. The system used a series capacitor between the antenna and the radio equipment, which blocked the lightning stroke energy. A shunt gap to the aircraft structure bypassed the lightning energy harmlessly to the aircraft skin. The spark gaps had a replaceable cartridge with brass sperical electrodes to indicate the charge transfer and a small magnetic link cartridge to record the current peaks. A shunt resistance was used across the spark gap to bypass p-static charge to the aircraft skin without producing radio interference.

Damage to radio equipment was completely eliminated by the installation of these lightning arrestors. With later antenna installations using integral insulated aircraft sections, the lightning arrestor became more important to flight safety by preventing structural damage as well as maintaining communications.

Lightning strikes are most prevalent at extremities and gross protrusions of an airborne vehicle (Figure 18-6). These areas include the nose, tail, wing tips, leading edges of wing-mounted jet engines, external tanks, stabilizer tips, and top edges of fin and rudder. The fuselage and other engine areas are seldom subjected to more than a rearward-swept stroke, which usually causes minor damage. Inboard wing and tail areas have the lowest probability of direct lightning damage. Consistent with these generalizations, inadequately protected radomes, tail-mounted detecting equipment, and wing-tip fuel tanks are prime and vulnerable targets.

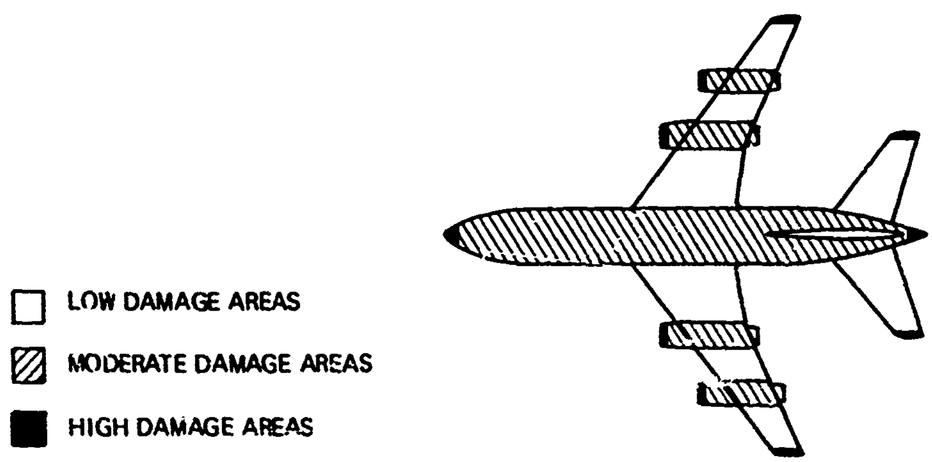


FIGURE 18-6 AREAS OF LIGHTNING STRIKE PROBABILITY

Radome Damage

Radome damage is usually the most serious and, next to fuel-vapor ignition, occurs most frequently. If the radome surface is punctured, moisture may be admitted and air pressure may be lost. Either can contribute to degradation of radar performance. If the radar is part of a terrain avoidance, terrain-following, fire control, or similar system, lightning can thus impair the mission. If the radome is shattered by the explosive force of lightning penetrating it, not only will the fragile dish and electronic circuitry be damaged, but pieces of the radome may be ingested into the engine or damage the control surfaces of the tail section.

To divert lightning across radomes not already protected, adhesive-backed aluminum tape is sometimes applied externally to the radome surfaces, with one end of each strip grounded to the aluminum skin of the aircraft (Figure 18-7). Ordinarily, only one end should be grounded so as to minimize radar beam degradation and pattern distortion. Avoid as much as possible, running the strips parallel to the plane of polarization of the antennas inside the radome. This technique should be considered as a one-shot type of protection, since each bolt of lightning will vaporize at least one aluminum strip. Aluminum tape 3 to 8 mils thick and 3/8 to 1/2 inch wide is generally used. This protection method is usually avoided in new designs because lightning-caused explosive vaporization of a strip tends to split the radome along the line of the strip. Such strips are also fragile and suffer from erosion. When barely-visible cracks occur and isolate portions of the strips from the bond to the aircraft skin, p-static sparking across these cracks causes very severe interference.

A reliable and durable solution to lightning damage to radomes is the use of solid metal strips attached to the outside surface of the dielectric. They should lie parallel to the slipstream and at right angles to the polarization of the enclosed antennas. They should be positioned every 30 to 45 degrees around the axis depending upon radom size, and to avoid gaps greater than about 1/8 inch between strips. The strips must be capable of carrying instantaneous currents of up to 200,000 amperes without fusing. Medium strength aluminum stock 1/8 by 3/8 inch, with fasteners every three to five inches has been found adequate. In addition to using the fasteners, it may also be good to cement the strips securely to the radome, since large tearing stresses are involved when lightning tracks along the radome surface and hits the strips from a tangential direction. The strips should also be electrically bonded to the aircraft skin or a carefully designed grounding manifold, using a transition plate to minimize tearing. Several stout fasteners should be provided to carry the current and to distribute it to prevent fusing of the metal at the point of contact at the airframe. Sharp bends in the strips must be avoided. Bends of 90 degrees are unacceptable, unless a particular design is adequately qualified.

Experience has shown it is essential to divert lightning so that it remains outside a radome. If the lightning stroke penetrates the radome to reach a virtually grounded antenna, equipment, or frame, the forces and temperatures can disintegrate the dielectric or cause delamination or tearing over an extended

area. Once entrapped, the high-energy column heats the air to 27,000°F. in the lightning channel itself. The resulting quick expansion causes explosive pressures measuring as high as 150 psi. This may result in many thousands of pounds pressure over a nose type radome 50 or 60 inches in diameter that may shatter the enclosure or blow it off the front of the aircraft.

If antennas or other sensors or equipments are tailmounted within a nonconducting protective canopy, the probability of lightning damage is very high. Here it is inadvisable to use aluminum tape, as the stroke attachment point previously described cannot be swept farther aft. Multiple strokes following the same path result in extensive melting and burning unless solid conductive strips are used and properly installed. Placement of the strips depends upon the polarization of the antennas or other RF sensors.

Any nonconductive protruding areas such as astrodomes or canopies can be protected from lightning by a ridge-mounted metallic conductor or, if large, by additional conductors in pairs mounted midway in the side areas. Such conductors attached outside the insulator in a properly designed and tested installation will shield personnel or equipment. This is clearly specified in MIL-B-5087B(1).

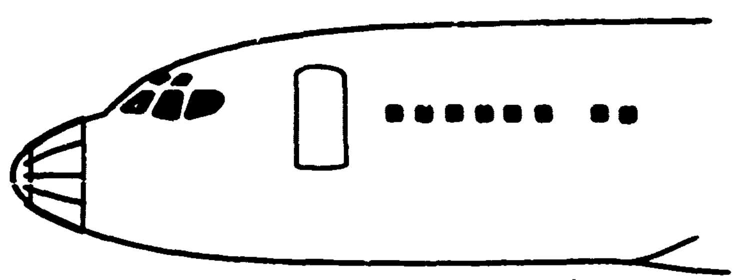


FIGURE 18-7 STRIPS APPLIED TO RADOME FOR LIGHTNING DIVERSION

Damage To Composite Materials

Some new lightweight composite materials being tried experimentally in aircraft construction have proved to be quite vulnerable to lightning damage. Lightning entering composite materials produces damage both at the surface and within. For instance, the new boron-fiber reinforced composite panels are found to suffer alarming loss of strength after exposure to artifical lightning in levels far below the high amperage of natural lightning. The damage may not even be visible, so post-flight inspection is a problem. Laminates enclosing honeycomb cores become fractured and delaminated. Cores of aluminum become vaporized internally, producing a firecracker-effect explosive force that amplifies the damage. To keep lightning from penetrating composite panels, aluminum coatings (flame-sprayed in 6-mil thickness) have shown fair protective qualities.

The durability of such coatings is not known, but where coatings are burned by lightning, and segments or islands are isolated electrically, the resulting condition is favorable for disruptive p-static generation. Composite materials, even those heavily coated by conductive films, have been found to be inferior to riveted aluminum aircraft skin in diverting lightning currents away from mangetically-sensitive devices.

Conductive paint containing silver particles is also available as a protective coating against lightning damage. This is a one-shot protection and tests show a limited effectiveness. A problem is the creation of static due to cracks in the paint coating. These cracks result from flexing of the surfaces or from direct lightning hits that evaporate the metal at the strike point and craze it farther out. A paint coating 0.01 inches thick will never approach the protection given by a 0.06 inch aluminum skin. Moreover, silver around aluminum invites corrosion.

Another form of one-shot protective coating sometimes applied over wing openings and over aluminum skin at wing tips is known as "armor plate." It consists of a layer of resin-impregnated fiberglass cloth covered with 0.01 inch aluminum foil. This gives sheet aluminum a protection equal to that obtained by more than doubling the thickness of the aluminum skin. The armor plate protects the vulnerable areas by diverting the lightning current and blast away from the regions of conductive aluminum vapor over a tough dielectric. The thin aluminum skin armor plate must be replaced after a stroke. The success of this method lies in preventing the lightning from penetrating the surface or its current from flowing across a joint incapable of carrying it without sparking. Cracks and burns may exist in the foil remaining after a strike, creating islands of ungrounded metal previously described as a source of electromagnetic interference due to corona discharge.

Damage To Adhesive Bonds

Among the new techniques for fabricating metal aircraft is the use of adhesive bonds. Construction costs are reduced by a decrease in component complexity, while structural strength-to-weight ratios are increased by eliminating row fasteners and their unavoidable stress concentrations. Attempts to lower the resistance of the joints by using conductive-cement fillers or conductive tape overlays are under study. This has been satisfactory for providing a low resistance ground plane for effective radio transmission and for controlling the accumulation of electric charges leading to p-static generation, but the current-carrying requirement accompanying lightning discharges has not been satisfied.

Arcing that occurs with adhesive-bonded construction may appear on the outside or the inside, or it may take place within the bonded joint itself. In each case, specific hazards arise. These will all be more fully discussed, except for external arcing, which has already been mentioned. It should be noted that the voltage across the joint just before arcing will be on the order of 1000 volts, since the thickness of the cement layer in the joints is between two and ten

thousandths of an inch and electrical breakdown of this layer will limit the voltage.

Arcing on the inside of the aircraft skin can be hazardous in several respects. If arcing occurs near fuel tanks, the hazards are obvious, especially if the tanks are of adhesive-bonded construction and permit instantaneous pulses to appear across the joints on the inside of the tanks. Studies are being conducted on the control of explosive conditions within fuel tanks. It has been established that when oxygen concentration is held to less than 11 percent in the vapor space, flame cannot exist. Inert gases are being used, but the most effective fire prevention appears to be in deoxidizing the fuel by a process known as scrubbing, either on the ground or in flight to remove the oxygen that may be liberated as the aircraft climbs to high altitudes. Every effort should be made to prevent any possibility of arcing within fuel tanks.

Arcing within adhesive bonds as a result of a lightning strike is a potential hazard. The electrical arc may ionize trapped air or vaporize the bonding material to generate explosive pressures (Figure 18-8). Large sealant fillets, at least 3/16 of an inch diagonal should be used to avoid internal arcing. The airworthiness of aircraft may be jeopardized if primary load-carrying structures experience such adhesive bond separation. The probability of this occurrence is increased when conductive filler is used. Metal fasteners such as rivets can be used with some types of adhesively bonded joints to minimize the electrical discontinuity of the surface skin of aircraft. Several fasteners per linear foot may reduce resistance to acceptable levels yet retain much of the desired simplicity of construction. Short bonding jumpers, described in Chapter 11, should be installed at every structural adhesive-bonded joint. These jumpers should be placed so as to maintain a straight path whenever possible. Even with the jumpers this type of construction is not recommended in fuel-vapor areas that may be subject to lightning-current flow.

Internal Damage

The electrical skin effect that keeps RF currents from penetrating deeper than a few thousandths of an inch in a metallic conductor, operates also with lightning discharges. Any discontinuity that may attempt to channel lightning current or guide it in a devious route results in a voltage difference, often breaking down in an arc bridging the discontinuity. Ideally, the metallic skin of the air vehicle should have continuous metal-to-metal contact at the mating surfaces of each panel. The traditional riveted stringer-frame construction has proved to be a good basic electromagnetic shield. A skin of such relatively high conductivity allows heavy amperage to flow freely across the surface, protecting electronic systems and personnel, who are often unaware of a direct lightning strike.

If inadequate surface protection or serious electrical discontinuities in the skin of a vehicle permit lightning to penetrate, the heavy current may do considerable internal damage. In small aircraft especially, it can blast its way through lightweight materials, fusing cables, exploding batteries, and burning out

electronic equipment tied to the power bus or other wiring. Larger aircraft with a complete metallic skin covering may experience entry of lightning via antennas, sensors for air speed and temperature, improperly bonded access doors, and other irregularities.

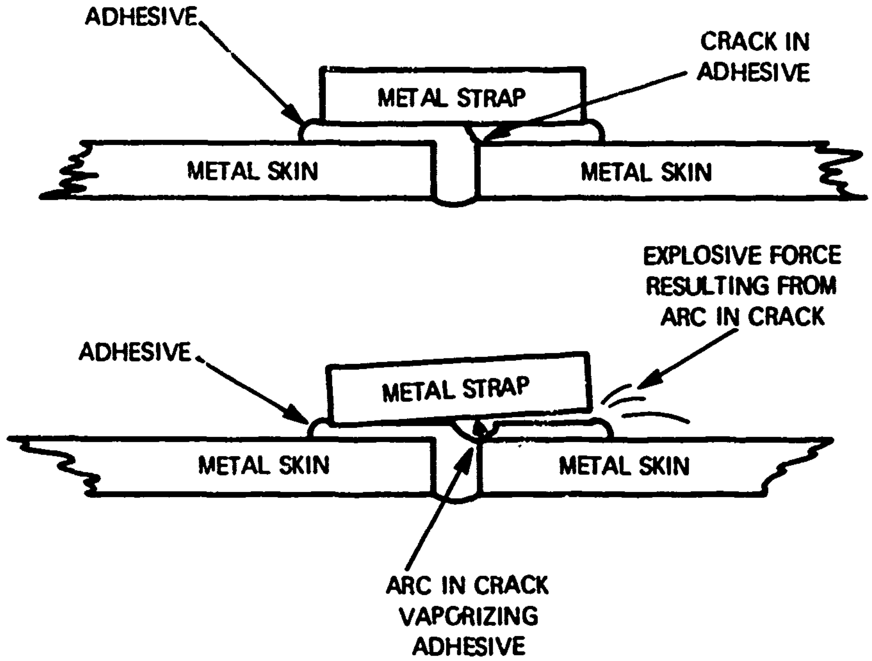


FIGURE 18-8 ADHESIVE BONDED STRAP JOINT DAMAGED BY INTERNAL ARC ACCOMPANYING LIGHTNING STRIKE

Mechanical moving joints may be subject to lightning damage. Control surface hinges should be jumpered by approved jumpers. Access doors to critical areas such as fuel tanks should be placed in relatively safe areas and should be so designed that electrical bonds at the joints are truly metal-to-metal all around. All such joints should be well isolated from fuel-vapor regions. Hydraulic lines and hydraulic rams also should receive grounding attention, as heavy lightning amperage, frequently entering associated control surfaces, may burn or blow out fluid seals. Wing-tip fuel tanks are highly vulnerable targets. Protection must be provided by measures such as lightning diverters and thick-wall metal skin on the one hand and on the other by a fuel line valve and special latch that is resistant to the welding effects of a high surge current and welding of moving parts. All welded construction of fuel tanks is preferable to fabricated sectioning.

Bonding jumpers of copper braid or flat sheet-metal strips are recommended for grounding all electronic equipment to the airframe. MIL-B-5087B(ASG) graphs the ratios between joint resistance and amperage flow capable of causing enough heat to ignite explosive vapors. It illustrates the

necessity of isolating fuel tanks from a direct discharge path and the need for arc-proof bonding seams.

Lightning arrestors are recommended at receiving and transmitting antenna entry points. Aircraft lightning arrestors do not protect the equipment from voltage transients, only against large lightning stroke energies. Coaxial cable itself can provide some degree of protection when bends are incorporated to discourage lightning from following the outside of the cable. Wiring to electric heaters, motors, navigation lights, and sensors such as fuel gages should be run in well-grounded conduits. This prevents lightning from inducing damaging voltage transients into the equipment or from following along and fusing exposed leads and interconnected units.

The same uncontrolled lightning pulses appearing in ground loops may damage integrated circuits. The potential danger of such pulses may escape detection in ground tests, being masked by copper cable bonding jumpers and low resistance adhesive fillers. It should be noted that the time constant associated with the inductive impedance of jumpers or the resistance of carbon adhesive bond fillers may permit a significant instantaneous voltage difference when the input pulse has a rate of rise of 10,000 to 100,000 amperes per microsecond which is characteristic of a lightning transient. Bondjumpers do not protect against inductive drop potentials.

An indirect but serious consequence of lightning interference is its magnetizing effect on steel and ferrous alloys that may make the magnetic compass useless. After a lightning strike, the pilot should immediately check the correlation between the magnetic compass and a functioning directional gyro. He may have to use alternate means of navigation. Portable magnetic check-out and degaussing devices are available for use by the ground crew following a known or suspected lightning strike. Composite materials, even heavily coated by conductive films, are inferior to riveted aluminum aircraft skin in providing an electrically conductive path at a distance from magnetically sensitive devices so that the magnetic field generated by a lightning discharge will not adversely affect the magnetic devices.

Another indirect and equally serious result of the magnetic field accompanying a lightning discharge is the erasure of magnetic recording tapes and magnetic computer memories. Tapes and memory banks should be well shielded when installed in equipment as well as in ready storage compartments.

REPORT OF INCIDENTS

Aircraft losses attributed to lightning have been remarkably few. All-metal aircraft construction with electrically bonded and riveted seams has undoubtedly contributed to the safety of both personnel and electronic equipment. This type of construction provides an effective Faraday shield that keeps electrostatic charges on the surface, as do lightning discharge currents.

Published reports, released after thorough accident investigations, have reduced the number of commercial aircraft accidents attributed to direct lightning strikes to only two in the past several decades. Statistics released by the

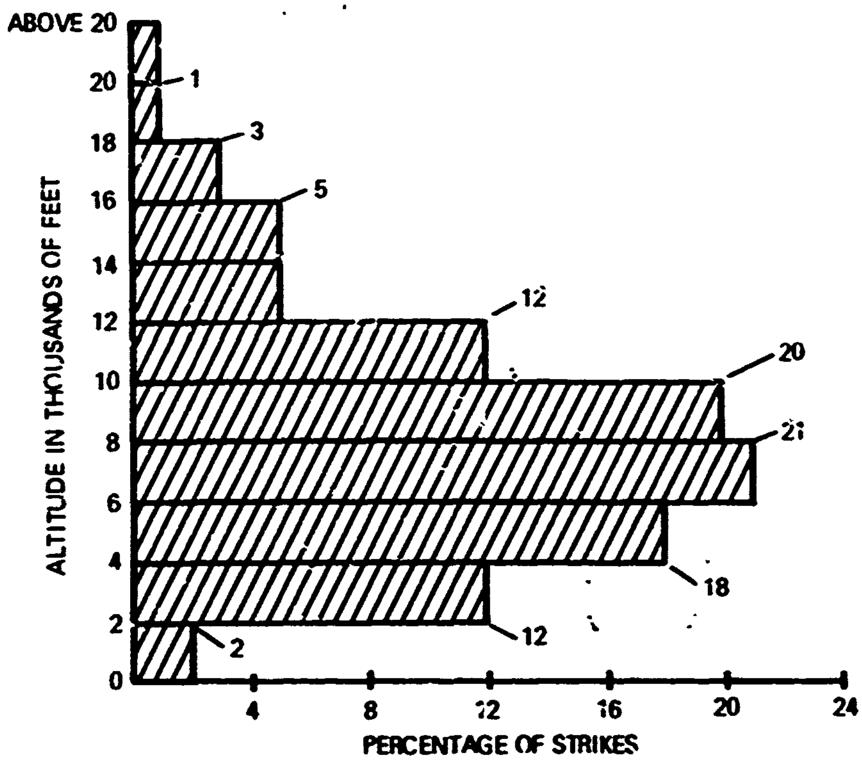
U. S. Air Force point to only one lightning-caused major accident in the last ten years. These statistics attest to the effectiveness of lightning-protection efforts.

After extensive study of the much-publicized 1963 crash of a Boeing 707 near Elkton, Maryland, the accident was attributed to ignition of fuel vapor in a wing tank as result of a lightning strike. Tests on a fuel tank access door of a similar jet transport, performed in the laboratory with man-made lightning, showed that internal arcing took place at the door seal even though a bonding jumper had been installed. The inductive effect of the jumper, when subjected to an extremely fast discharge simulating lightning, developed a voltage drop high enough to arc across a phenolic rub-strip on the inside. A knitted wire mesh gasket used in a redesign of the tank access door permitted the electric discharge to flow across the wing surface with no significant voltage drop within the tank.

While the above redesign removed one hazard, it may also have caused another hazard. In this case, a fuel tank inspection panel was repainted in such a way that the paint film created high resistance at the seal. Subsequently, in-flight p-static charging of the insulated panel caused corona discharge and severe electromagnetic interference. Fortunately, careful investigation uncovered the problem before an explosion occurred.

Each new design presents new problems. The swept-wing configuration of supersonic jet transports already has presented unanticipated shifts in lightning strike probabilities as shown by simulated lightning tests. The new fighter-interceptor aircraft moving-wing designs will present problems due to vulnerability of the movable joints. Venting fuel tanks at higher altitudes and the use of heated fuel may present more design problems.

Although supersonic jet transports spend most of their flight time in high altitude regions of low lightning probability, they still run the gamut of thunderstorms in landing, take off, and holding. Reports of lightning strikes compiled from commercial airlines and the U. S. Air Force, summarized in Figure 18-9, show the altitude and temperature ranges within the majority of reported lightning strikes have taken place. It seems impractical to count on avoiding lightning strikes or to dismiss them on the basis of low probability. Rather, lightning should be respected and dealt with as an ever-present hazard demanding consideration at every level of air vehicle design.



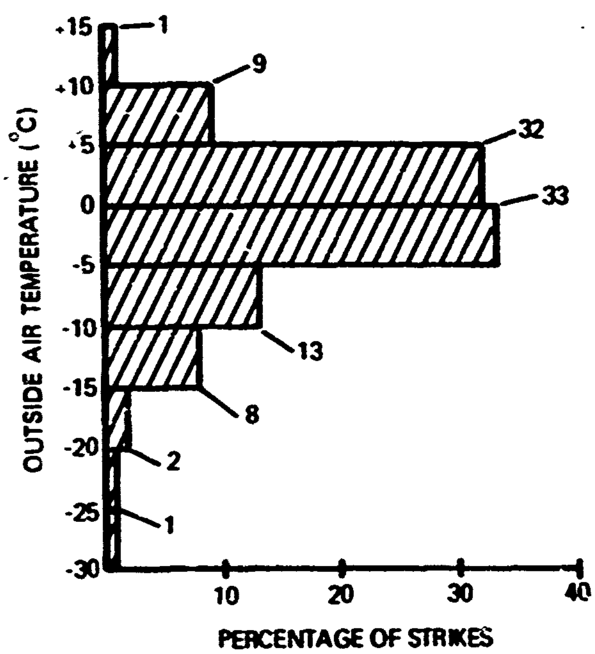


FIGURE 18-9 DISTRIBUTION OF LIGHTNING STRIKES RELATIVE TO ALTITUDE AND TEMPERATURE

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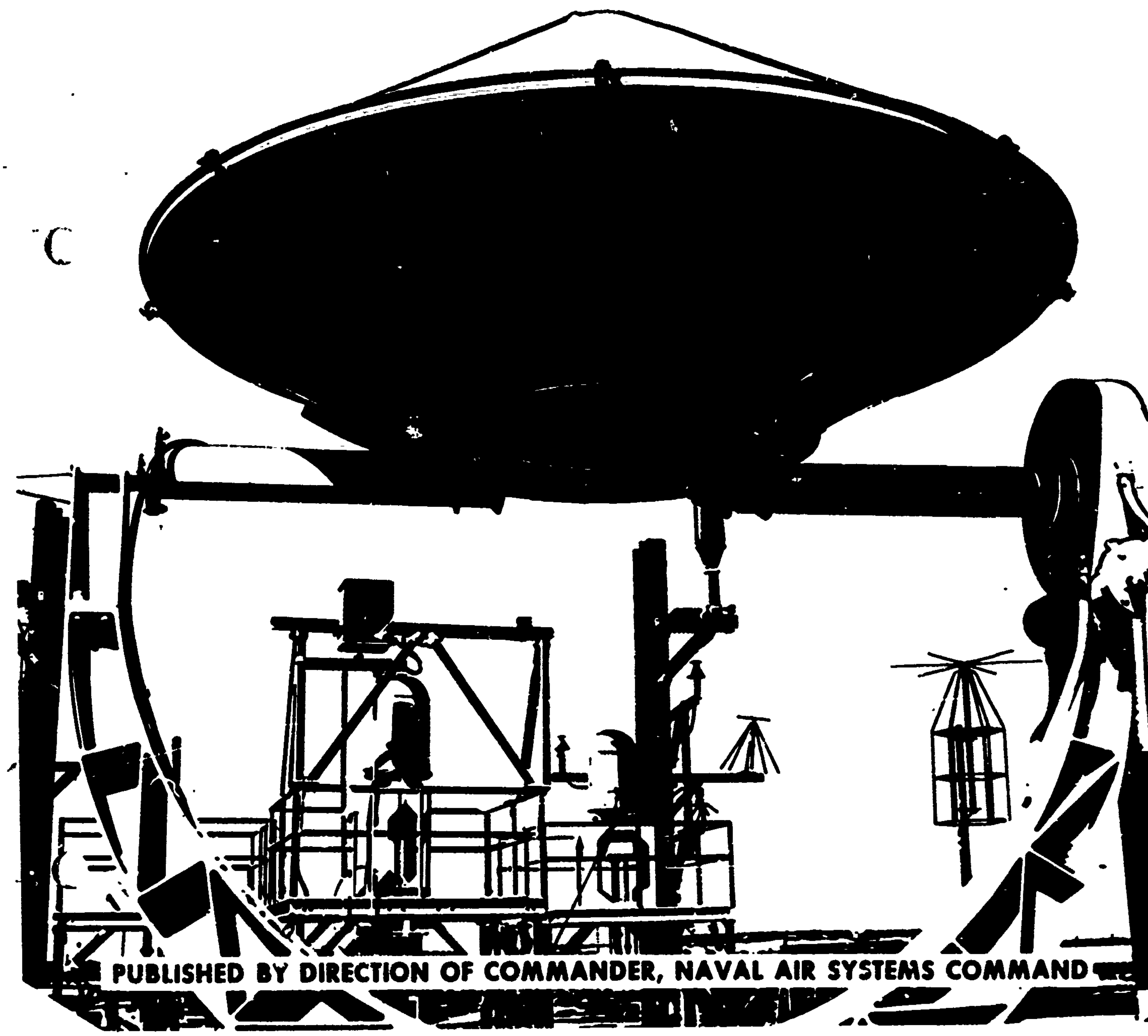
ELECTROMAGNETIC COMPATIBILITY MANUAL

CHAPTER 19



PUBLISHED BY DIRECTION OF COMMANDER, NAVAL AIR SYSTEMS COMMAND

CHAPTER 19
EMC APPLICATION ENGINEERING FOR MAINTENANCE AND OPERATIONAL PERSONNEL

CONTENTS

ENGINEERING GUIDELINES

Aircraft operations depend heavily upon the capabilities of avionics systems for collecting, processing, and disseminating information, and for controlling weapons and forces. The presence of electromagnetic interference in an avionics system will degrade the information being processed. Degradation of avionic capabilities results in impairment of combat effectiveness; therefore system engineering requires achievement of electromagnetic compatibility so that the unwanted influences of one device or circuit upon another are held to a minimum.

As the capability and mobility of military weapon systems increase, there is a corresponding increase in complexity, power output, and radio spectrum occupancy of avionics systems to meet operational requirements. Each increase in information-handling capability also increases the probability of either causing interference or being susceptible to interference. Systems performance effectiveness is affected by the electromagnetic compatibility of components of a system with each other and with the environment in which they operate.

Electromagnetic interference is an inherent part of the total dynamic environment of any electromechanical, electrical, or electronic system. Present and future requirements for increased aircraft and equipment capability have caused systems engineers to intensify the investigation of radio interference phenomena, sources, and measurements. There are many possible sources and causes of interference in a modern aircraft, and this calls for continuous and coordinated effort to solve interference problems. Interference control measures to achieve compatibility are applied throughout the aircraft, and maintenance and operation personnel should be cognizant of them so as to avoid impairing their effectiveness by improper operation or maintenance. Furthermore, maintenance and operation personnel may discover, in the course of normal use of the aircraft, additional EMC problems not adequately identified or resolved in previous stages of design or modification. Information concerning such discrepancies must be brought to the attention of appropriate authorities so that corrective action can be taken.

The vast majority of electronic systems used by the U.S. Navy are information handling devices. These devices can be grouped into general categories:

1. Communication devices, which include voice, telegraph, radio teletype, data link systems, IFF/SIF
2. Detection and tracking sensors, which include radar, AEW, underwater sound, MAD, ECM, infrared
3. Navigation devices, which include TACAN, LORAN, INS, VOR, ADF, ILS
4. Data processing and storage devices, which include analog and digital computers, encoder/decoders, tactical data systems, tape recorders
5. Control devices, which include missile guidance, electronic gunsights and bombsights, autopilots, electromechanical actuators, servomechanisms, magnetic amplifiers
6. Reconnaissance and warning devices, which include infrared, white light, photographic systems, laser electro-optical systems, ECM detectors
7. Instrumentation and display devices, which include CRT's, flight instruments, warning indicators

Interference can be defined as a phenomenon that tends to impair the orderly detection and/or processing of information. Information can be anything from an electrical impulse to voice communication. Electromagnetic interference, therefore, refers to an electrical or magnetic signal that disrupts the flow or processing of information or intelligence.

From the viewpoint of the weapon system engineer, there are three phases in planning an interference-free system:

1. Prediction of interference based on known data and measurements concerning systems performance effectiveness, ambient electromagnetic environment, propagation paths, and frequency data
2. Engineering of the system for maximum compatibility with the electromagnetic environment based on data obtained in 1. above
3. After system development, reduction of interference not previously predicted and eliminated

There are many factors in systems development that must be reconciled, including cost, performance requirements, frequency assignments, and compatibility among the various equipments of the system and with equipments of outside systems. These factors require detailed consideration, and for the most part each is related to the others. The system must therefore be planned so as to obtain optimum system effectiveness, using all the information that can be obtained on the equipments that comprise the system, the frequencies used, the normal operating environment, and the system capability requirements.

A new weapon system is introduced into the Fleet only after many hours of design, test, and evaluation. Final acceptance by the Navy is made after extensive flight and simulated flight operation during Navy Preliminary Evaluation (NPE) and Board of Inspection and Survey (BIS) trials. Because these trials involve a number of groups, each having specialized interests and each

competing for aircraft time in which to accomplish its tests, it may not be possible to conduct detailed EMC checks under as wide a variety of conditions as the compatibility representative would desire. Furthermore, small variations in production may cause individual aircraft to differ slightly from those subjected to type acceptance tests. Therefore, operational organizations may receive aircraft with EMC deficiencies not fully corrected. Once a system becomes operational, Fleet experience will reveal whether the weapon system can fulfill its assigned operational requirements. If deficiencies in compatibility become evident, further EMC control measures such as modifications or retrofits may become necessary.

SYSTEMS PERFORMANCE EFFECTIVENESS

Effective performance of systems in the Fleet has always been an important factor in the successful accomplishment of the Navy's missions. The tremendous growth in system complexity due to demanding operational requirements and to rapidly advancing scientific knowledge has magnified the problem of obtaining effective performance from the new systems being delivered.

The complexity explosion has not been restricted to the electronics systems alone, however. Enemy threats are more complex, decision time is reduced, tactical decisions are more critical, available time to act is reduced. These factors tend to require increased complexity in all the systems that combine to form a combat capability. The seemingly simple task of collecting weapons control data, for example, has increased to a point where the complex Naval Tactical Data System (NTDS) is required. More complex systems in turn generate greater technical and operational interference problems. Consequently, achievement of satisfactory systems performance effectiveness in the Fleet has presented design and maintenance personnel with a serious challenge.

Systems performance effectiveness can be defined as, "A measure of the extent to which a system can be expected to complete its assigned mission within an established time frame under stated environmental conditions." For example, the design capability of a radar-weapon system may consist of being able to detect an object at a certain distance, classify the object, track it precisely, and contribute to the accurate delivery of appropriate weapons onto the target. Any reduction of system capability due to the lack of compatibility of subsystems with each other or with the system environment will reduce systems performance effectiveness. The presence of interference in a radar or other sensor may reduce the range at which a target can be detected, or delay target classification, or reduce the accuracy of target tracking and weapon control.

Data for future programs depends in part upon retrieval of experience and data from operating units. This information is collected through the Maintenance Data Collection System (MDCS) carried out under the Naval Aviation Maintenance and Material Management (3-M) program set forth in OPNAVINST 4700.16B and NAVAIRINST 4700.2. Attempts are being made to change the MDCS data collecting forms so that the necessary inputs regarding

systems performance effectiveness can be obtained from the MDCS without additional reporting requirements. If these efforts are successful, the project manager of new systems under development or existing systems will have available to him the main body of experience and experimental data from operational systems, which can then be used in designing a new system or improving an existing one. These data are needed for two principal reasons:

1. They enable a project manager to evaluate past decisions in the light of performance effectiveness. He can then determine the adequacy of weighting and other judgement factors that were applied in the preceding phases. An added return is the recording and sharing of these evaluations with project managers of other systems being planned or developed.
2. These data can also be used to establish decision baselines for determining the need for improving operating systems and for evaluating proposed changes. Costly changes and changes of questionable return may result from use of inadequate or incomplete data.

INDICATIONS OF EMI

EMI can produce effects ranging from minor annoyance to the air crew to complete failure of a mission or loss of the aircraft. In electrical or electronic systems that provide an audible or visible output, EMI may reveal its presence and give some clue as to its source. An audible hum, buzz, pop, frying or tearing sound in the aircraft IC system should indicate possible EMI trouble. Visual displays such as CRT's, gauges, counters, or warning lights that are erratic or flicker may indicate deleterious effects of EMI. Indications of EMI may be perceived when aircraft electromechanical servo systems are affected; electromagnetic interference to the stall warning circuits may induce a "stick shake" indication, or interference with control or automatic stabilization circuits may disturb the aircraft flight path. Deductive reasoning, and use of ON-OFF or MODE switches of suspected sources, may make it possible to confirm that the trouble is indeed EMI and narrow the field down to the offending unit.

However, all such indications are not necessarily caused by EMI sources within the aircraft. The causes may be troubles other than EMI, or the source may be external to the aircraft. Flight crews should therefore learn to conduct analytical investigations to determine the cause of the trouble when it occurs. It is not sufficient merely to return the aircraft to the flight line with a notation on the "yellow sheet" that, for example, "TACAN breaks range lock." Amplifying statements concerning the circumstances under which the TACAN breaks range lock should be included to enable the technicians to locate the true cause of the deficiency. Many a "black box" has spent futile hours on the test bench while the technician conducted detailed checks on it for troubles that turned out to be

EMI from some device not even related to the one being checked. A more useful description of the trouble in the above example would have been to say, "TACAN breaks range lock when IFF is interrogated."

Far more difficult to recognize are those EMI problems that produce no clear indication of their presence except when checks are made against another indication known to be reliable. This form of degraded performance due to EMI may consist of desensitization of a sensing element such as a data link receiver, or a steady value of error bias applied to a servomechanism or a fuel quantity gauge, or bit errors introduced into a digital system, or increase of circle of error in an ordnance system. When there is no obvious outward indication of degraded performance, the presence and degrading influence of EMI may remain undetected, or its effects attributed to something else. For example, if an aircraft compass heading differs from its radio homing heading (ADF, TACAN, VOR) by an amount other than the calculated correction factors, it is all too easy to charge the error to something like faulty determination of drift or deviation. Yet it is possible for EMI to have adverse effects on the accuracy of the magnetic compass or the radio homing device.

Present methods of Fleet maintenance are deficient in detecting and correcting EMI problems because maintenance of operational aircraft does not include testing whole systems against electromagnetic compatibility standards. Intermediate or rework maintenance is accomplished by pulling subsystems from the aircraft and performing bench checks on individual equipments. If an equipment measures up to sensitivity, power output, and other principal parameters, it is designated as satisfactory and returned to the same or different aircraft with no determination of its compatibility with other equipments in the aircraft or with the environment in which the aircraft will operate. Organizational maintenance is largely "GO – NO GO" preflight and periodic tests of individual subsystems or equipments against relatively simple standards, with no determination of the extent to which each system is the cause of, or is susceptible to, EMI involving other systems in the aircraft or in the aircraft environment. In fact, intermediate and organizational maintenance groups have no convenient way to conduct realistic tests on compatibility of all systems in the aircraft with each other and with the aircraft environment, and must rely on the observations of flight crew members who may not be proficient in detecting, analyzing and reporting EMC deficiencies. At present, no tests are conducted to determine the reduction of accuracy, reliability, operating range, "kill" probability, and other performance parameters attributable to EMI when the complete aircraft is functioning as a weapon system under operational conditions.

EMI CAUSES AND EFFECTS

No device that uses electrical energy is entirely free of unwanted electromagnetic emission or susceptibility. The acceptability of EMI levels is dependent on the degree to which the effects of EMI are felt. EMI levels are unacceptable if unwanted radiation or susceptibility is sufficient to cause an effect or disturbance greater than certain specified limits. As the state of the art

improves, and as greater demands are placed upon military electronics systems, limits become more stringent.

In general there are two sources of electromagnetic interference. They are:

1. *Natural* - EMI caused by natural phenomena such as electrical storms, triboelectricity from rain and dust particles, and radiation from the sun and outer space
2. *Man-Made* - EMI from man-made sources such as electrical or electronic equipments. This is the major source of interference with which this chapter is concerned

Man-made interference arises from three possible causes. Interference from functional sources is that caused by signals generated to perform a useful function but which cause interference as a normal consequence of this function. Radio communications or radar systems, for example, must radiate in order to function. Such emissions can be modified and controlled to minimize interference, but they cannot be eliminated without also eliminating their useful function.

Incidental EMI is that caused by sources of interference not specifically designed to generate electromagnetic energy, but which cause EMI in the normal course of their operation. Interference such as that caused by ignition systems, motors, relays, and inverters is incidental interference. This type of interference can often be suppressed without eliminating the useful function of the device that caused it.

The third cause of man-made interference is spurious EMI. This can be spurious emission such as transmitter harmonic energy, parasitic oscillation, unwanted mixer products, or modulation splatter, or spurious susceptibility such as receiver images, IF feed-through, or other responses due to the manner in which signals are processed in the receiver. Spurious interference can also be the consequence of RF currents flowing in a metallic junction having nonlinear conduction characteristics. A non-linear junction excited by an RF field will cause harmonics to be generated, or a series of cross-products to be generated if RF energy of more than one frequency is present.

In investigating the causes and effects of interference, EMI is designated by the way in which it is propagated, either as conducted interference along a conductive path, or as radiated interference in the form of an electrical and/or magnetic field. The cause-and-effect relationship appears in the designation to indicate whether it is emission of EMI that is of concern, or susceptibility of an affected device. Therefore, EMI causes and effects, and consequently the test procedures and corrective measures, are divided into four categories:

CE = Conducted emission in which interfering energy leaves the source along a conductive path

CS = Conducted susceptibility in which the interfering energy enters the affected device by a conductive path

RE = Radiated emission in which the interfering energy leaves the source as a radiated electromagnetic field

RS = Radiated susceptibility in which the interfering energy enters the susceptible device via a radiated electromagnetic field

Radiated emission or susceptibility can be described in terms of circuit impedance or energy field. A high impedance circuit is voltage sensitive and is primarily susceptible to electric field energy or emits it. Its dominant EMI-coupling mode is capacitive. A low impedance circuit is current sensitive and is susceptible to, or an emitter of, magnetic field energy. Its primary EMI-coupling mode is inductive.

The EMI-coupling mode may not be the same as the mode in which the wanted signal is handled. For example, a signal circuit using twisted pair in which instantaneous signal currents travel in opposite directions in each conductor, may look like a low impedance to the signal, but the EMI energy may see the twisted pair as a two-wire circuit having a high impedance with respect to a ground plane, in which EMI currents travel in the same diection in each conductor. A converse condition could also occur: a high impedance circuit with braided copper shielding against electric fields may nevertheless function to couple magnetic field EMI inductively.

EXAMPLES OF EMI

To illustrate the wide range of possibilities, the following actual cases of significant EMI are listed. While many of the cases mentioned were discovered during BIS trials (after engineering was supposedly complete), some were found after the aircraft involved had become operational, and it is entirely possible that yet other EMI problems in any of the aircraft remain unsolved and will show up unexpectedly under certain conditions and combinations of equipments, frequencies, and operating modes.

UHF Communications: On the West Coast, a large number of incidents were reported of noise interference to military UHF channels, especially the UHF emergency/guard channel, of sufficient magnitude to render the channel unusable. The source was found to be household garage door openers. The type of garage door opener involved used a super-regenerative receiver that radiated appreciable energy, and that was highly susceptible to received energy. Enough garage door openers were used in the area to disrupt completely the tower and GCA use of the emergency/guard channel over a wide area and constitute a serious hazard to aviation. It was also found that aircraft transmitting on the UHF guard channel caused the garage doors to open, which could be dangerous to anything in the path of the door.

HF Communications: HF transmissions disabled the autopilot and caused rapid oscillation of aircraft control surfaces. Another type of HF transmitter caused false indications on the oxygen quantity gauge. Transmission on certain frequencies lit the master caution light and static discharge light. In another type aircraft, operation of the HF transmitter caused extreme interference to the Automatic Direction Finder (ADF).

ECM Warning Receiver: This receiver, a part of the integrated warning and display system, intentionally uses a wideband "front end." Transmissions on

certain UHF channels disrupted the use of the receiver. The radar beacon system in the aircraft also produced severe audio and video interference in the EMC warning receiver. Simultaneous operation of the radio altimeter and the secure communications system caused intermodulation interference in the ECM warning receiver, producing visual and aural malfunction.

Defensive ECM Transmitter/Receiver: Transmission on certain IFF modes caused extreme interference to the defensive ECM (DECM) equipment. Transmission from the DECM transmitter also interfered with IFF replies. Nose and tail DECM equipments were capable of triggering and answering each other when set off by a random noise pulse. In some configurations, DECM equipment caused continuous illumination of ECM tail warning panel lights, with severe audio disturbance.

Secure Communications System: Transmissions from secure communications system on certain channels interfered with the ECM warning receiver and with IFF. On certain channels it caused TACAN to break lock.

TACAN: Transmissions on certain TACAN channels caused triggering of IFF and precluded use of the missile guidance system. TACAN also interfered with reception and identification on the ECM search receivers, and interfered with ECM warning receiver video display. On certain HF communications channels, aural response to TACAN PRF interference was troublesome.

IFF: Transmission from TACAN, DECM transmitter, and secure communications system interfered with IFF replies.

Missile Guidance: Operation of IFF, TACAN, or DECM transmitters produced moderate to severe interference with the missile guidance system.

Radio Altimeter: The radio altimeter could trigger the DECM transmitter, which in turn interfered with the ECM warning receiver. Radio altimeter emission was capable of causing illumination of certain warning lights in the ECM warning receiver system. An ECM search operator tried to track a spurious response to the radio altimeter in his own aircraft. The radio altimeter interfered with certain channels of the AEW data link system.

Bomb/Attack Radar: Operation of the bomb/attack radar in certain modes caused undesirable audio responses in the ECM search receiver. It also caused the ECM warning receiver to fail to recognize certain valid signals. Another model of bomb/attack radar also caused objectionable interference in the ECM search receiver and, when the chaff dispenser was in the AUTO mode, caused chaff packets to be ejected continuously.

ECM Jammers: Operation of jammers precluded the use of the bomb/attack radar, and caused triggering of the DECM transmitters.

IC System: Power supply rectifiers produced objectionable interference at 400 or 1200 Hz. The interference level increased when TACAN was turned on, or when UHF was in the HOT MIC mode, or when the computer was selected on the missile control panel, or when the anticollision lights were operated. Operation of the AUTO TEMP control produced disturbing transients in the IC system.

Flaps: Operation of flaps caused the engine overheat warning lights to illuminate, and caused false indications on the vertical speed indicator.

True Airspeed Indicator: Transmission on certain UHF channels produced random variations in units and tens digits of TAS indicator.

RESOLUTION OF EMI PROBLEMS

An effective approach to compatibility problems requires knowledge of EMI causes and effects. Three general methods of EMI/EMS control are generally considered: attacking EMI at the source, or along the propagation path, or at the victim device. It is usually best to take corrective action at the source of EMI because one source can affect a number of susceptible devices. However, this approach is not always feasible.

EMI can usually be reduced to tolerable limits by one or more of the measures discussed below. Because design features built into the aircraft for control of EMI/EMS can become degraded in the course of aircraft operation and maintenance, flight and ground crews should learn to recognize the function of EMI control measures and take appropriate action to preserve EMC.

SHIELDED ENCLOSURES

A shielded enclosure is used to control EMI by surrounding an interference source or susceptible circuit. The shield acts as a filter to electromagnetic fields by creating an impedance mismatch to the field, reflecting part of the field and absorbing part. Careful consideration must be given to proper closure of the shielding structure. Finger contact stock or braided RF gasket material is frequently used at closure edges to inhibit leakage of EMI. Mating surfaces of closures, whether or not finger stock or RF gaskets are used, must be clean and contaminants such as paint, oil, preservatives, or oxides removed to provide good electrical contact. All closure fasteners must be in place and tightened to proper torsion. Any discontinuity presented to RF currents at closure edges can act as a slot antenna for EMI. Broken finger stock, distorted RF gaskets, or missing screws must be replaced, and mating surfaces kept clean.

Ventilation louvres or ports through shielded enclosures pose a special problem. To keep such openings from acting as slot antennas, wire mesh or honeycomb air filters are used to permit passage of air while acting as an RF shield. Air filters must be cleaned often to maintain proper ventilation, but they must be removed and replaced carefully to prevent degrading of shielding effectiveness. Special shielding measures are also used when a meter, CRT, fuseholder, or other device penetrates a shielded enclosure. A shielded part should never be replaced with an unshielded part.

EMI CONTROL FEATURES OF WIRES AND CABLES

Because airframe and equipment wires and cables need to be repaired, replaced, or relocated from time to time, maintenance personnel who perform

these tasks should be familiar with the EMI control measures involved. In general, airframe and equipment wires carry not only signal, power, or control voltages, but they can act unintentionally as pickup probes and transmission media for EMI. The EMI-coupling action of a wire can be entirely different from its intended function. For example, an exhaust gas temperature probe in the tailpipe may act as an antenna for EMI and its electrical cable can couple EMI into susceptible equipments in the aircraft unless precautions are taken.

Shields for wires and cables function in the same manner as for enclosures. Braided-wire loom is the form most frequently used. The effectiveness of braided shielding becomes degraded through breaking or spreading of braid strands, usually because of frequent flexing, short-radius bends, or improper use of cable clamps. The principal trouble spot is the point at which a shielded cable enters a connector or other terminating device. Cable runs should never be used for handholds or steps.

Because wire braid shielding, more so than solid shielding, is an imperfect EMI control measure, high energy cables often require special treatment. Antenna cables and radar pulse cables should be kept separated from other wires, and extra precautions regarding flexing and short-radius bends should be observed. Antenna and pulse cables are often of special construction, using such features as double-braided shields, silver-plated braid wires, conductive rubber anti-corona "skin", or wire armor over the outside of the cable. Such a cable must not be replaced with one of lower grade.

On interconnection cables, EMI can be controlled and reduced by using two-wire combinations for critical applications. The two wires are usually twisted together, and may also be enclosed within a shield. The two-wire combination may take either of two forms:

1. A critical wire and a ground wire used as a pair
2. An electrically-balanced pair of wires interconnecting a source and a load that are either floating free of ground or balanced electrically with respect to ground

The wire pair should retain its identity in cables and connectors in order to retain its EMI-control capability. When new or replacement cables are fabricated, certain guidelines should be followed:

1. The ground member of a pair should never be made to serve as the ground return for another circuit.
2. The greater the number of twists per unit length, the greater the reduction of EMI.
3. Shielded wire pairs in the critical category for EMI emission or susceptibility should preferably be the only wires in the shield.
4. The shield or ground return wire should be grounded at a single point if the interference problem involves low-frequency energy, less than 50 kHz. Multiple-point grounding should be used when high-frequency EMI is involved.
5. One wire of the pair should not be separated from the other at any point so as to form a magnetic coupling loop for EMI.
6. Unused wires in cables and wire bundles, and the connectors at the

terminating ends, should be grounded in accordance with 4. above so that they do not act as a propagation medium for EMI.

BONDING AND GROUNDING

A bond is a direct electrical connection that prevents or reduces to a negligible amount any potential difference between connected points, of which one point is usually a ground reference plane. A good electrical bond presents the lowest possible impedance between the connected points at any frequency of concern. A satisfactory bond for direct current may be ineffective at RF. In general, braided or stranded bonding conductors exhibit higher impedance than solid conductors of comparable size, and their use for bonding should be restricted to those applications in which flexibility is an overriding consideration. This may call for special instruction for electrical and mechanical maintenance personnel who are not familiar with the behavior of bonding conductors at radio frequencies.

The best bond is a short, straight, wide, solid conductor with a welded junction at each end. Impedance of the bond is increased by use of braided or stranded conductors, conductors of small surface area, or conductors bent into a U-shape. A bolted or riveted bond junction exhibits higher resistance than a welded junction.

If a bolted or riveted bond must be used in maintenance, the mating surfaces must be cleaned each time the bond is restored, so that it is kept free of contaminants such as oil, paint, preservatives, and oxides. It is necessary to remove metal burrs, chips, sandpaper particles, or anything else that would prevent proper contact over a large area. A bolted or riveted bond junction should be tight enough to prevent the intrusion of anything such as water or oil, which would impair the quality of the bonding junction or destroy it. This requirement may call for treating the junction with a protective coating once the joint is made, especially if dissimilar metals are joined. The effective edition of MIL-B-5087 provides detailed specifications for electrical bonding in aerospace systems.

Because the skin and structural members of an airframe serve as a common ground plane to which all systems in the aircraft are grounded, good bonding practices must be observed when repairing or replacing parts of the airframe.

At present, adequate test equipment for measuring the effectiveness of a bond or ground connection is not available to shipboard or avionic shop personnel. Maintenance personnel should become familiar with bonding and grounding requirements set forth in Military Standards and Specifications and in other parts of this publication, so that they become proficient in visually checking bonds and grounds. Visual checks performed conscientiously, are a useful part of maintenance.

FILTERING

An electrical filter is a network that transfers electrical energy in its passband and rejects or absorbs energy in its stopbands. Most filters are

three-terminal devices having input, output and ground connections for each circuit involved.

Three-terminal filters may take such varied forms as coaxial feedthrough capacitors, choke-and-capacitor networks, and antenna multicouplers. Two-terminal filters include bypass capacitors other than feedthrough types, series or shunt wavetraps, and simple chokes A filter may be an integral part of an assembly or it may be a separate device. In either case, two precautions must be observed if the filter is to perform its function effectively.

1. No path must be allowed to exist whereby EMI can be coupled around the filter. EMI "sneak" circuits include unused wires in wire bundles, unused pins in connectors, stray capacitive or inductive coupling, and breaks or openings in shielding.
2. The path to ground must be of the lowest possible impedance. The filter should preferrably be welded or soldered to the ground (or shield) frame: if bolted or riveted, the mating surfaces should be treated as described for bonding.

AMPLITUDE LIMITING

An amplitude limiter is a nonlinear device that prevents signal levels from exceeding a specific value. Amplitude limiters are used to prevent certain voltage or current levels from rising high enough to create an interference problem. An amplitude limiter may be used in the audio stages (and sometimes the RF stages) of a transmitter to prevent overmodulation and consequently adjacent channel interference. Amplitude limiters are also used in AM receivers to prevent EMI impulses from exceeding the amplitude of the wanted signal and in FM receivers to wipe out amplitude variations that may be caused in part by EMI.

An amplitude limiter may also be used across an inductive load such as a relay or motor so that the "inductive kick" when the device is deenergized is not allowed to develop an appreciable EMI transient.

Maintenance of amplitude limiting devices involves two considerations:

1. Because the diode type amplitude limiter acts in effect as a peak absorption device, it may become damaged in the course of performing its intended function. A routine check of its effectiveness is often difficult especially if it is enclosed in a sealed housing with the relay or motor. Yet defective diodes must be located and replaced to preserve EMI control.
2. The effectiveness of transmitter or receiver amplitude limiters depends upon the setting of gain controls that preceed the limiter. Gain should be set so that the peak amplitude of a normal wanted signal barely reaches, or drives slightly into, the limiting point. Lesser signal levels do not provide fully effective protection from the interference signal, and greater levels cause undesired distortion of the wanted signal.

BANDWIDTH LIMITING

Bandwidth limiting is the process by which the emission spectrum or

response admittance band is confined to specific frequency limits by appropriate bandpass filters. Excessive bandwidth, either for transmission or reception, leads to adjacent-channel interference.

Bandwidth limiting in a transmitter is largely a matter of controlling the modulating wave. Rise and fall of modulation pulses can be shaped to avoid abrupt transitions, and high frequency components of audio or video complex waveforms can be attenuated. Maintenance considerations require that replacement components affecting modulation waveforms comply with original EMI-control specifications, and that modulation adjustments are such that overmodulation does not occur.

Bandwidth limiting in a receiver is largely a matter of selectivity and alignment of tuned bandpass circuits. Misalignment and improper tracking not only render the receiver less sensitive to the wanted signal, but also make it susceptible to EMI that otherwise would be further outside the bandpass. If the preselector section is misaligned, image rejection and suppression of oscillator radiation can also be degraded.

Most filters present an impedance discontinuity to unwanted energy so it is reflected back toward its source. For this reason, a filter used alone will not be sufficient for EMI control; adequate shielding between the input and output circuits will also be needed. Maintenance personnel must make sure that the filter and the shielding are working together to suppress EMI. Dissipative filters that absorb rather than reflect the unwanted energy are becoming available, but they are not yet widely used.

PHYSICAL SEPARATION

Physical separation consists of placing distance, and if possible an intervening structural member, between a source of EMI and a susceptible circuit in order to take advantage of EMI field attenuation afforded by the propagation path. Each antenna cable and pulse modulator cable should be isolated from all other wires and cables, and physical separation maintained over as much of the cable run as possible. Antennas should be separated as much as airframe design permits, and located, when feasible, so that antennas do not "look into" each other. Cabinets and racks housing equipments should be separated and oriented to minimize coupling of electric field and magnetic field energy between the equipments.

Maintenance personnel should be aware of the EMI-control attributes of cable separation, antenna characteristics, and equipment rack placement so that EMC is not degraded in repair or rework.

FREQUENCY SEPARATION

Frequency separation consists of placing systems capable of interfering with each other on different frequencies to achieve compatible use of the spectrum. Selecting best frequency channels for EMI reduction through channel separation involves planning at squadron or higher level or in certain cases, the international level. Maintenance or flight crew personnel may need to remind

planners of EMC requirements. Even though an equipment may be capable of tuning over a certain range, local conditions in various areas of the world may preclude using part of that range.

Frequency separation is absolutely necessary if two or more systems share an antenna through use of a multicoupler. The multicoupler, which essentially is a group of bandpass filters with each filter tuned to a particular frequency channel, must be in good condition to be effective. Frequency combinations selected to share an antenna through a multicoupler should be separated by an amount not less than 10 percent of channel frequency.

Frequency combinations to be avoided when planning channel separation are those that place a receiver of one system on or near the frequency of another's spurious emission (oscillator fundamental, harmonic, or unwanted mixer product) or that place a transmitter of one system on or near another's spurious response frequency (image, IF feed-through, or "birdie" response to receiver oscillator harmonics). Design engineers try to plan avionics equipments so that such combinations do not occur often, but in complex systems that cover wide frequency ranges it is impossible to avoid them altogether. A typical design approach might be to place a receiver's IF amplifier on, for example, 18.105 MHz (as in the AN/URR-35) so that the fewest possible spurious products fall within available channels. Similarly "odd" values are chosen by designers of other equipments. If the IF amplifier is not aligned accurately to the proper frequency, the effectiveness and compatibility of the receiver will be degraded.

Technicians performing alignment should know the precise frequency to which an IF strip should be aligned, and take special pains to keep alignment errors small. The usual shipboard signal generator seldom has adequate accuracy and stability of calibration to meet present day EMC requirements, and better accuracy may be needed than that provided by signal generator dial markings. It is therefore advisable to use a frequency counter to keep a signal generator on the proper alignment frequency. Alternatively, a crystal-controlled signal generator can be used.

Because exact frequencies are not specified for radars, frequencies can be separated within allowable limits by selecting and tuning the magnetron or other type of oscillator for best reduction of mutual interference between systems. However, allowable frequency bands are specified; in some areas of the world, exact frequencies are mandatory.

BLANKING, SYNCHRONIZING AND TIME-SHARING

Blanking is the process of inhibiting some stage of signal processing in a system for the period during which interference can occur. Blanking is used primarily to prevent transmitted or received impulses from introducing interference effects into signal detection, processing, or storage.

In some systems, blanking is a built-in feature of equipment design. In others, blanking must be supplied as an input from an external source. The blanker may operate at literally any point in the system. In a receiver, the farther from the antenna the interfering impulse is permitted to pass before it is

blanked, the longer must be the blanking period because additional stretching has taken place in each stage of signal processing. In a transmitter, blanking is usually accomplished by inhibiting the keying of the transmitter.

Synchronization as an EMI control technique consists of pulsing several radar, TACAN, or related transmitters together so that the emission from all transmitters takes place at a time when the receivers are not in use. This requires the use of a master synchronizer, and limits the several transmitters PRF's to values that are the same or integral multiples. The master synchronizer may also be the source of a blanking pulse to systems other than radar. In fact, the present trend in combat aircraft design is to use a programmed central multi-system synchronizer to provide blanking and synchronizing pulses.

Systems compatibility is sometimes achieved by operating two or more equipments on a time-sharing basis to avoid mutual interference. The equipments involved are programmed to operate alternately or in rotation. Usually each equipment is allowed an active emission period of several pulse intervals to update its data, during which the others are blanked so that their data is not disturbed by reception of EMI. Time sharing is commonly used to prevent loss of lock-on in TACAN, DECM, target acquisition, and data link system by alternating their active periods with those of IFF and radar systems that are likely to interfere. Maintenance checks consist of determining whether the ACTIVE/INHIBIT levels are present and of sufficient duration to permit adequate update during the ACTIVE period and to prevent the intrusion of EMI during the INHIBIT or BLANK period.

PROCEDURES FOR CORRECTIVE ACTION

Resources for aircraft maintenance and correction of deficiencies are provided the Fleet by many supporting organizations. Each of these activities is constantly trying to develop an accurate definition of the Fleet's changing needs, and each can satisfy only those needs that have been accurately and recently defined and communicated to the activity.

In the process of development, test, and introduction of new weapon systems to the Fleet, each supporting activity obtains a definition of the Fleet's needs for support of the new system. Despite the best planning efforts and the most enlightened and vigorous participation of Fleet personnel in the decisions, there is often a gap between the actual need and what is furnished to satisfy it.

Maintenance activities are plagued with many problems. These problems can be roughly divided into three categories:

1. Problems that the maintenance activities have the resources to solve.
2. Problems within the capability of the activity to solve (as individual problems) but which occur so frequently that the maintenance activity is unable to cope with the volume or frequency of their

occurrence. Frequent occurrence of similar problems indicates that there is a defect or weakness in the technical or logistics areas.

3. Those problems that are beyond the capability of the local activity to solve.

For every Fleet maintenance problem in the chronic or locally unsolvable categories above, someone either has the answer or is charged with the responsibility for obtaining and providing the answer or appropriate assistance. Area 7 of the DoD EMC Program set forth in SECDEF Directive 3222.3 with regard to operational EMC problems, requires that each Military Department be responsible for developing and implementing procedures and channels for detecting, reporting, solving, and correcting in the current time frame. NAVAIR Instruction 4700.2, "Naval Aircraft Maintenance Program," makes no specific provision for the EMC aspects of aircraft maintenance. EMC responsibility would seem to fall into an area overlapping paragraph 710b (quality control) and 710c (analysis) of the instruction. EMC maintenance on the part of operational maintenance organizations will require:

1. Procedures for detecting the channels for reporting electromagnetic incompatibilities that degrade flight vehicle effectiveness in the field
2. Application of existing measurement and analysis techniques to identify the sources of the problems and determine corrective action
3. Procedures for rapid implementation of required corrective action

The Standard Navy Maintenance and Material Management (3-M) System has three distinct parts: (1) the Planned Maintenance System (PMS), in which the technician carries out preventive maintenance according to instructions on individual Maintenance Requirement Cards (MRC) covering each piece of equipment; (2) the Maintenance Data Collection System (MDCS) through which the technician reports the problems he encounters in his corrective maintenance, the steps he takes toward their solution, and any need for further action that is beyond his capability at the time; and (3) a system of workload planning and control to improve management of intermediate level maintenance activities.

Two forms required in the MDCS are the Shipboard Maintenance Action (SMA) and the Deferred Action (DFA) forms. These forms are applicable to the work performed on site so that equipment can be evaluated.

To improve the Planned Maintenance System itself, the Planned Maintenance System Feedback Report, OPNAV Form 4700/7 provides a direct line of communication between the organizational maintenance technician and the Naval Material Command developer of the 3M system. This report is intended to point out apparent discrepancies, errors, or voids in some aspects of PMS, and to request new or replacement PMS software or hardware. The PMS Feedback Report is a means for submitting recommendations regarding maintenance procedures or particular test areas, which, among other things, may include EMC problems.

ON-THE-SITE FIXES

Engineering services are available from the engineering staffs of the Naval Air Systems Command Representatives, depot activities, and the Naval Air

Systems Command Headquarters. These services are available to all maintenance activities and include:

1. On-site engineering consultation
2. Assistance in prototyping special installations, mock-ups, or changes
3. Review and evaluation of changes and modifications proposed by the maintenance activity
4. Assistance in preparation of proposed changes or bulletins
5. Resolution of problems not discussed or provided for in manuals such as overhaul and structural repair handbooks

Depending on the nature and extent of the service required, these types of engineering services will be provided by either the cognizant NAVAIRSYSCOMREP, the depot activity assigned primary responsibility for manufacture or rework of the equipments involved, or the NAVPLANTREPO having contract administration cognizance over the company that manufactures the equipment.

These services can be obtained upon request from the cognizant Naval Air Systems Command Representative.

FIELD TEAM UTILIZATION

Each NAVAIR rework facility is provided a limited amount of money to establish field team service for special maintenance functions. Use of these field teams is scheduled by the Naval Air Systems Command Representative and coordinated by the Type Commanders. Field team service is usually restricted to incorporation of aircraft service changes and engineering fixes whose complexity or requirement for special tooling precludes incorporation by lower levels of maintenance. To save the time of field teams so that maximum effort can be spent on work that cannot be performed by lower levels of maintenance, field teams should not be required to perform tasks or any portion of tasks (such as disassembly or removal of equipments) that can be performed by organizational or intermediate maintenance activities. Specific instructions issued by Type Commanders provide procedures for requesting field team service. Operating units can obtain guidance from the Type Commanders of COMFAIR's/ CONFAIRWING's and from the Naval Air Systems Command Representative in solving problems requiring such service.

NAVY COMMAND ACTION (RETROFITS)

Current Fleet aircraft and the systems with which they are fitted are the product of dynamic technical research and development. Present technology is in a constant process of change, revision, and modification. New or additional missions may be developed for an aircraft to increase its versatility or to meet new threats. New weapons, airframe, or avoinic devices may be developed that better serve the intended mission. Such changes may alter the compatibility level designed into the aircraft or impose more stringent EMC requirements upon it. Operating forces should consider the effect of aircraft modifications upon compatibility, not only within the aircraft, but with the overall environment in

which the aircraft will operate.

A retrofit program may require that the aircraft be returned to the Naval Air Test Facility at Patuxent River for additional EMC tests and evaluation. A retrofit program performed under contract by a manufacturer should contain provisions for determining the effect of modification upon compatibility.

SUMMARY

EMI levels that could be tolerated in the era of relatively insensitive sensors in a sparsely-occupied spectrum are no longer acceptable in modern aircraft with large numbers of sensitive devices that must operate in close proximity to each other in terms of distance, frequency, emission type, and bandwidth.

EMC maintenance of aircraft systems is no less important than other characteristics such as sensitivity and reliability. However, EMC has one important difference: it is a requirement that must be met by the aircraft as a whole. A flight stabilization system and a radio communication system may each meet all requirements set forth in their respective maintenance handbooks when they are tested individually, yet when they are placed together in the same aircraft they may react upon each other severely to constitute a flight safety hazard. Or a glide path landing indicator may function perfectly until an instrument approach is made in an area that contains an FM or TV broadcast station to which the system became susceptible because an antenna connection was corroded or a ground strap was not restored properly.

Maintenance of aircraft systems to EMC standards is not expected to be a simple task. Detailed attention must be given to a large number of factors. However, electromagnetic compatibility (EMC) is interrelated to reliability, safety, capability, and other system characteristics, and EMC maintenance can and should proceed concurrently with them. Maintenance and operation personnel should learn to "think EMC" so that EMC deficiencies are noted early and corrected at the same time other maintenance requirements are met.

The purpose of this publication is to create an awareness of EMC requirements and to provide guidance for solution of EMC problems. Susceptible points of sensitive equipments have been pointed out, the sources and nature of unwanted emissions have been indicated, and means for controlling EMI have been discussed. Aircraft operation and maintenance personnel, as well as aircraft designers, should be familiar with EMC requirements so that deficiencies are detected early, reported promptly, and corrected effectively.

REFERENCES

1. *NAVMAT P3941A "Navy Systems Performance Effectiveness Manual." 1 July 1968*
2. *NAVAIR Digest (Various Issues)*
3. *OPNAV Instruction 4700.16C, 27 August 1965*
4. *NAVAIR Instruction 4700.2, 30 April 1968*